

THE NOVA EXPERIMENT

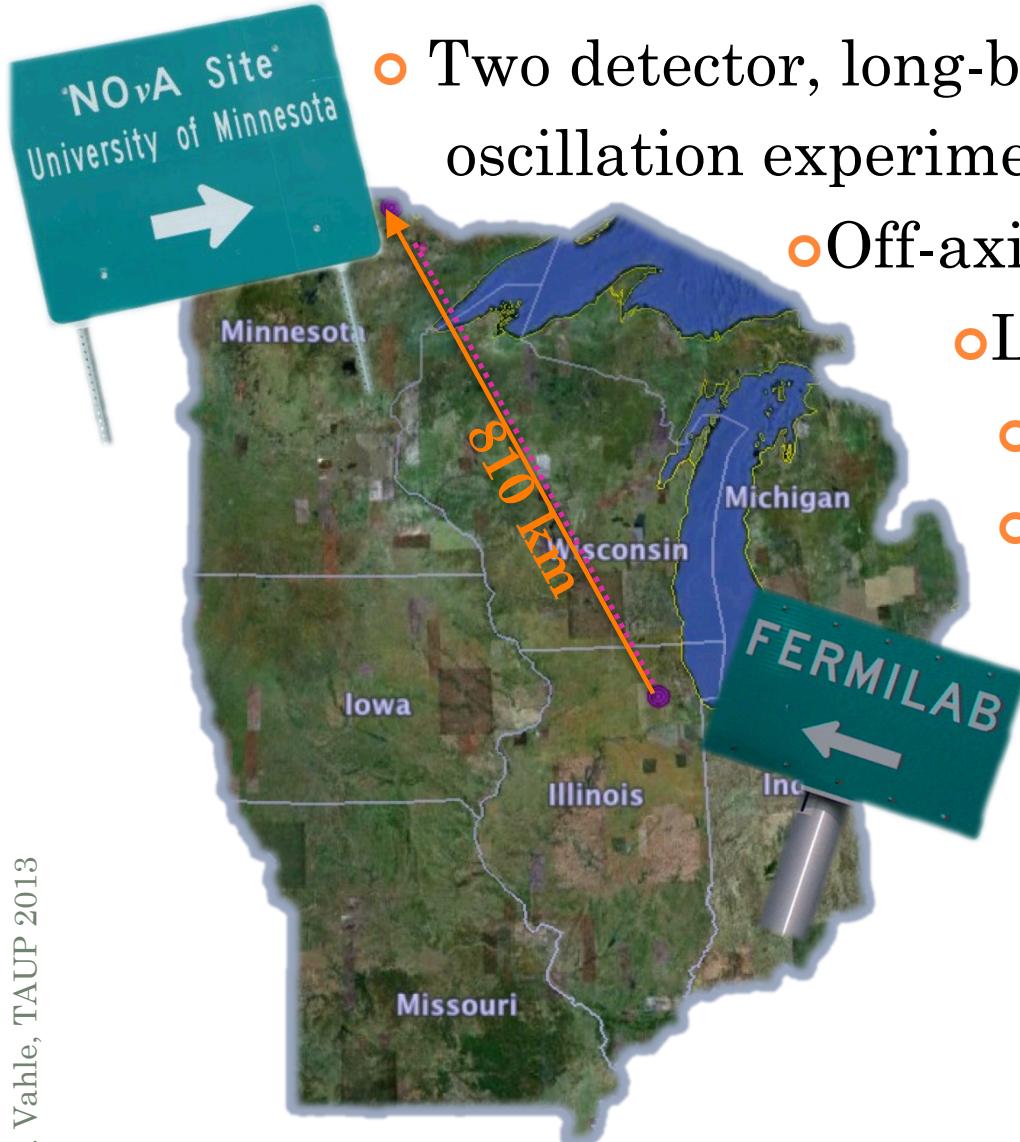
P. Vahle

College of William and Mary

Sept. 10, 2013



THE NOVA EXPERIMENT



- Two detector, long-baseline oscillation experiment
- Off-axis neutrinos from NuMI beam
- $L/E \sim 400 \text{ km/GeV}$,
- atmospheric Δm^2
- Physics goals:
 - Search for electron neutrino appearance (with both neutrinos and antineutrinos)
 - Precision studies of muon neutrino disappearance



THE NOVA DETECTORS



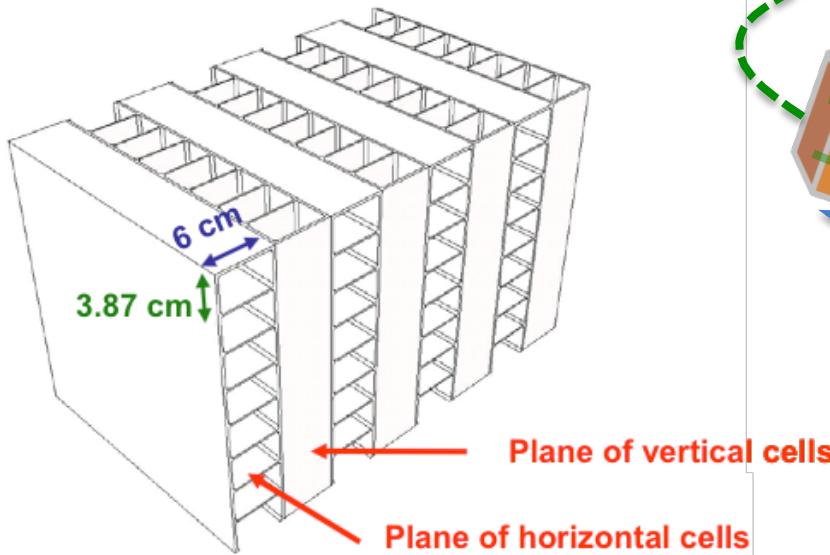
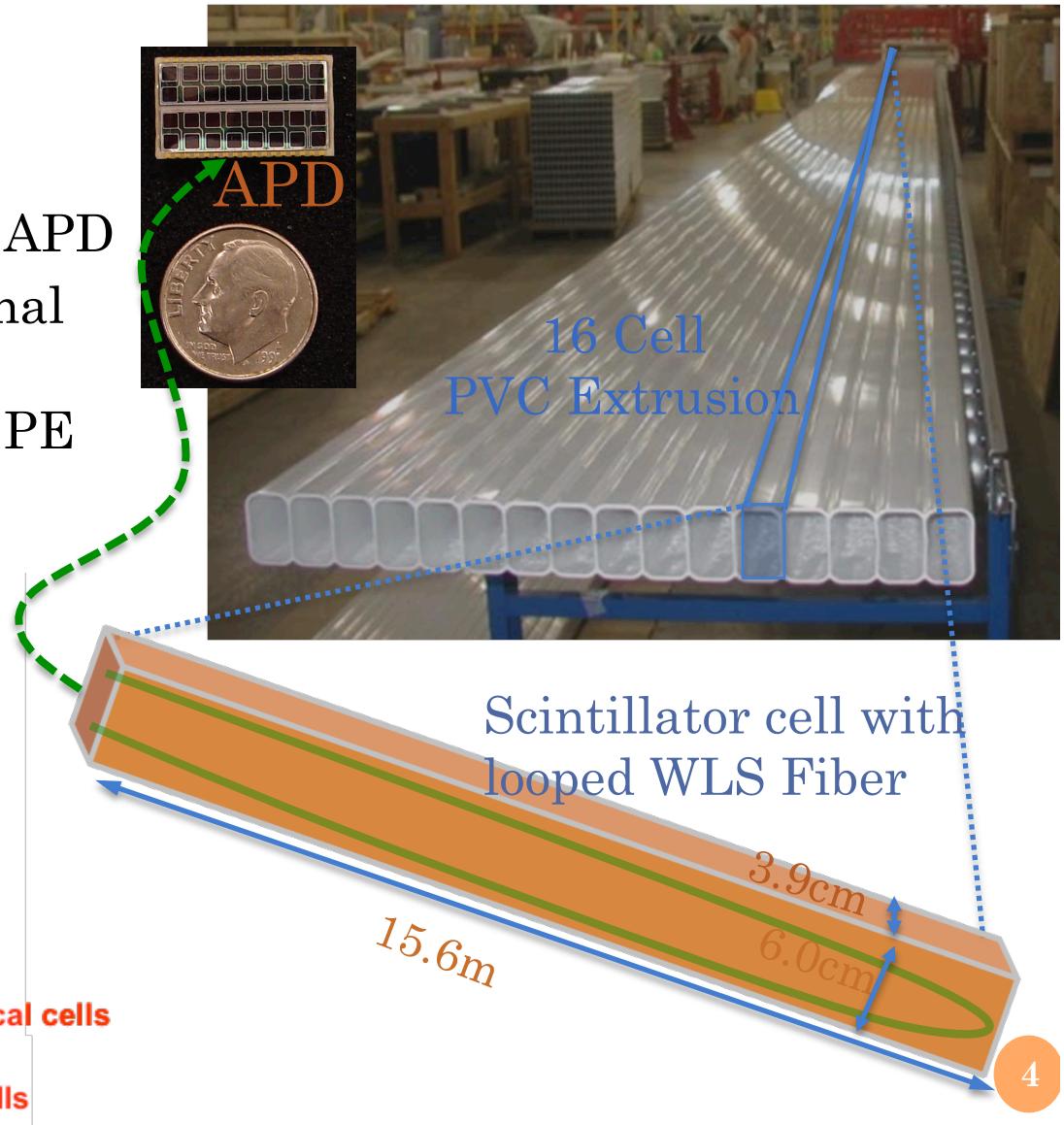
- Designed for electron ID
- Massive, Low-Z, 65% active
- FD: 14 kton, 810 km from source
- ND: 330 ton, 1 km from source
- Prototype Detector, on surface



DETECTOR TECHNOLOGY

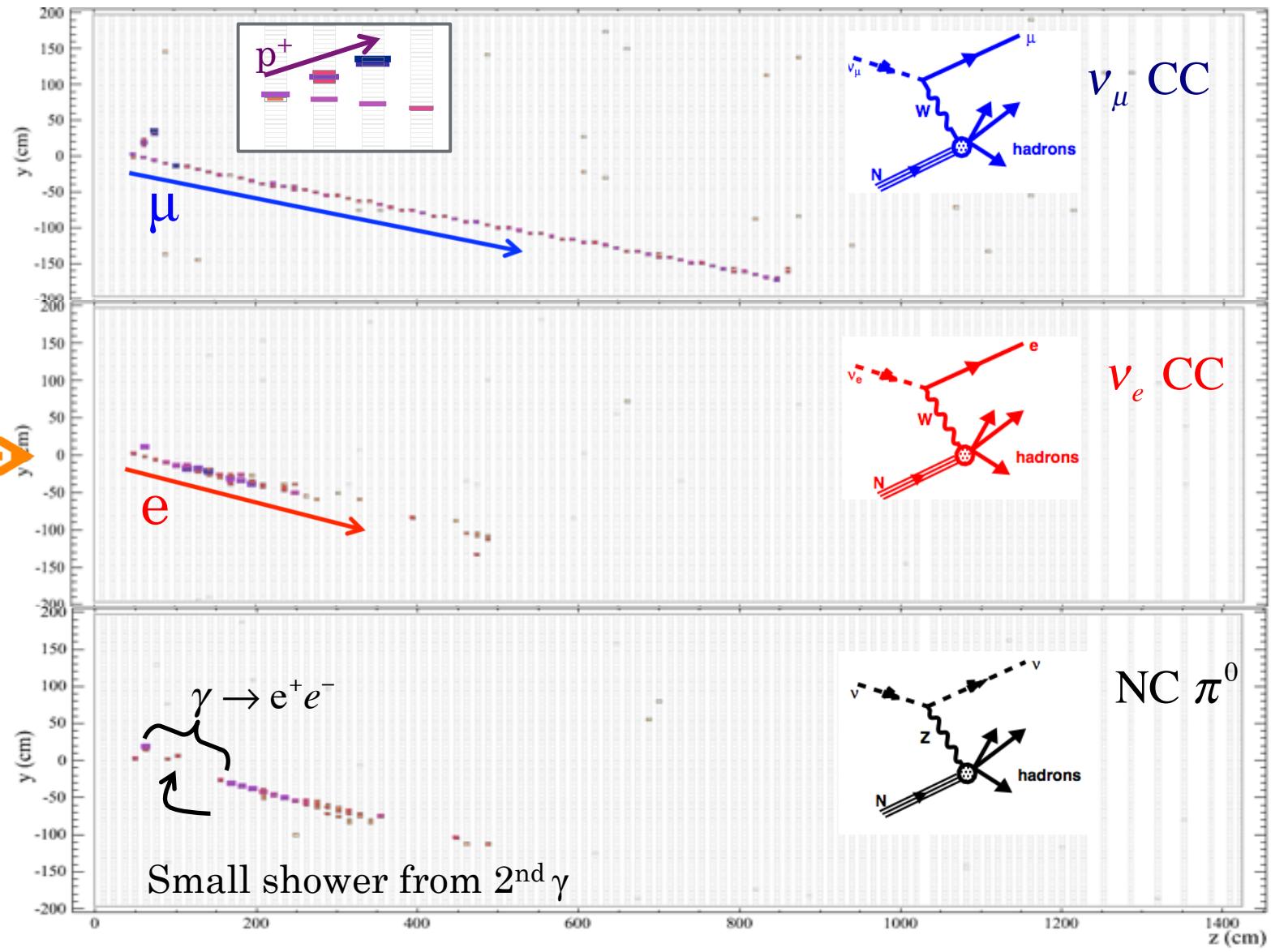


- PVC extrusion + Liquid Scintillator
 - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
- Layered planes of orthogonal views
- muon crossing far end=30 PE
- 0.15 X0 per layer



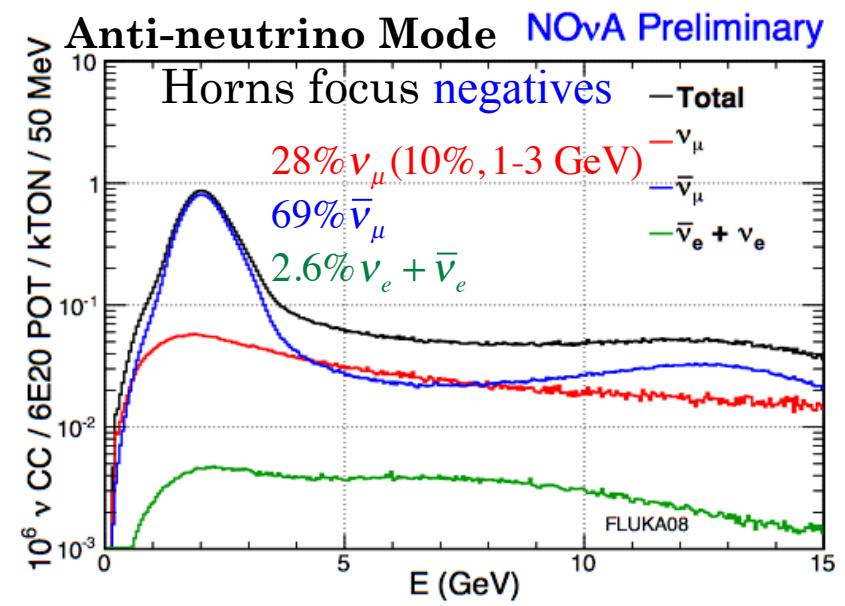
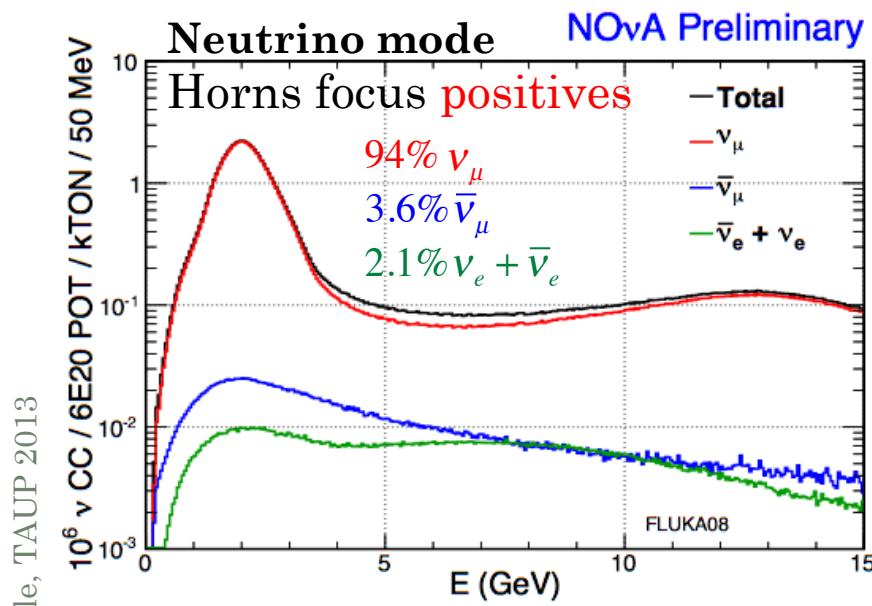
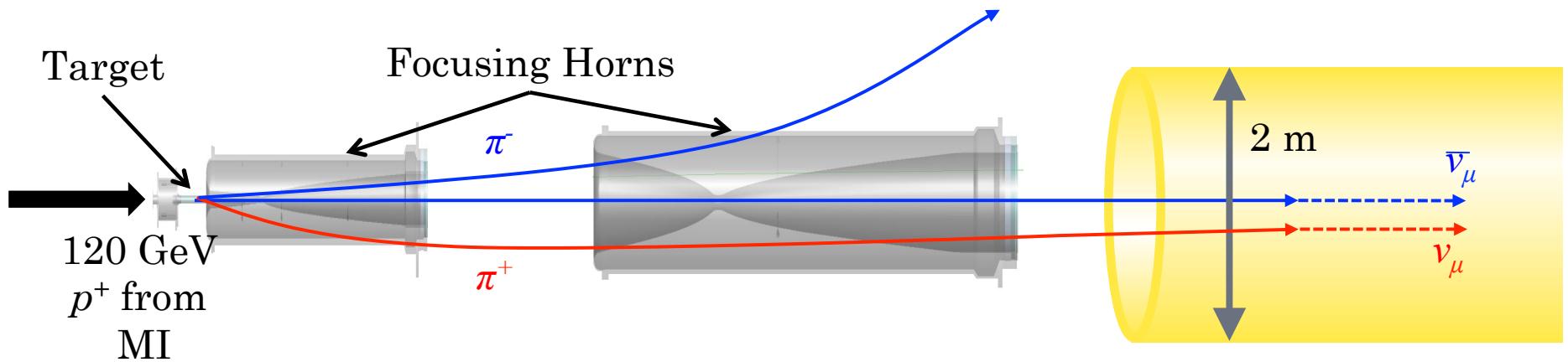


MC EVENTS IN NOVA





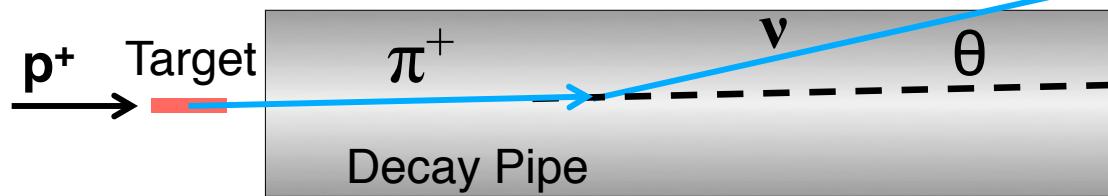
MAKING A NEUTRINO BEAM



See Poster by R. Schroeter

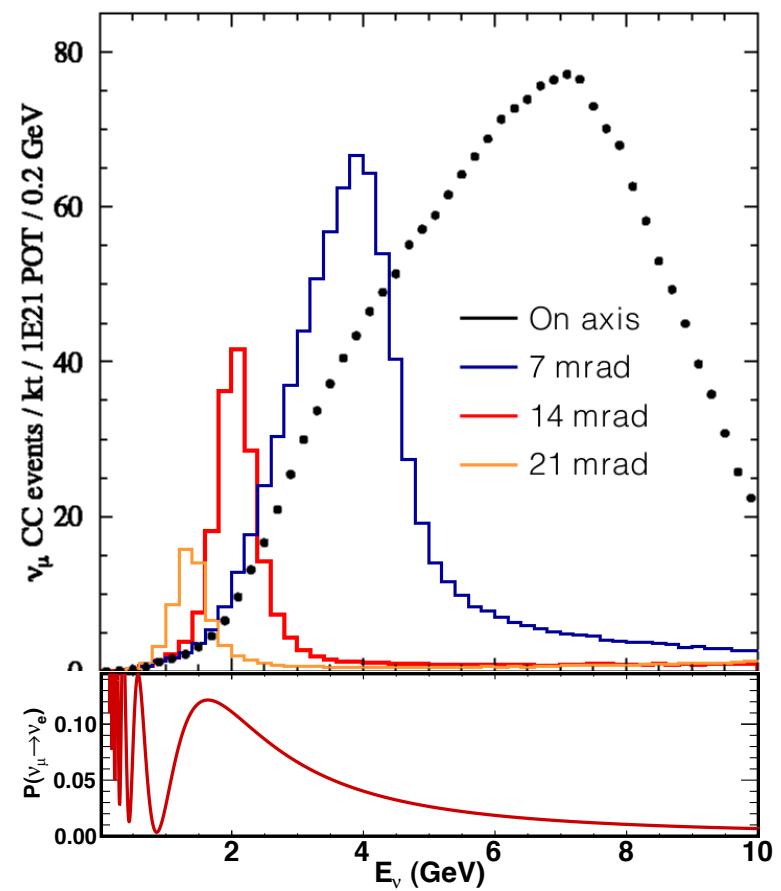
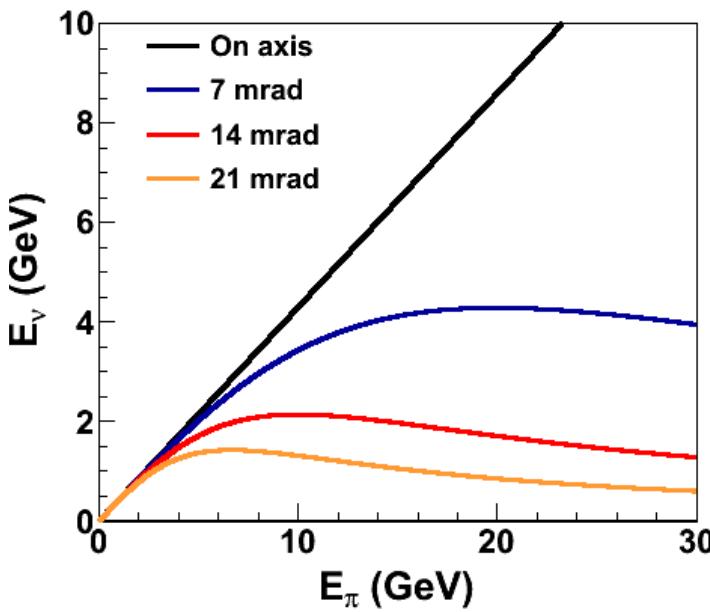


OFF-AXIS BEAM

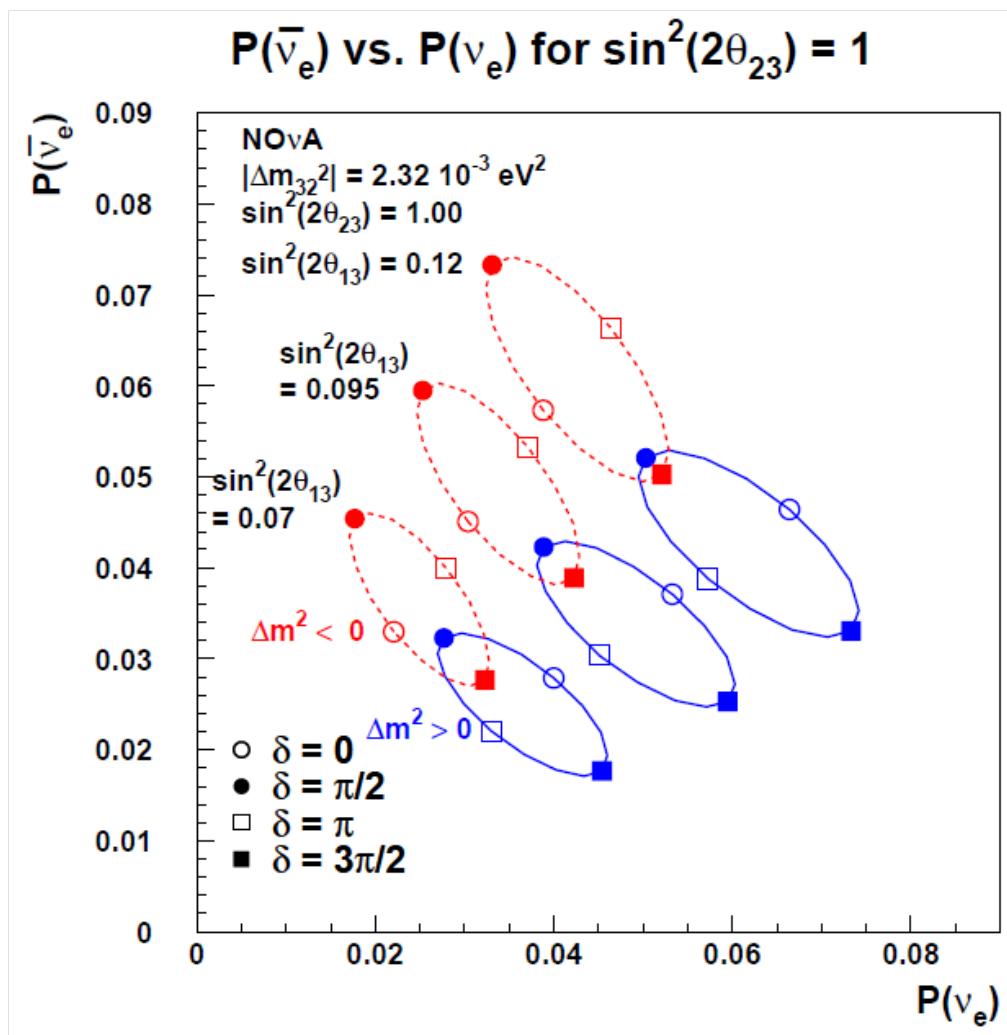


$$E_\nu \approx 0.43 \frac{E_\pi}{1 + \gamma^2 \theta_\nu^2}$$

- 14 mrad off-axis, narrow band beam peaked at 2 GeV
 - Near oscillation maximum
 - Few high energy NC background events



- Compare oscillation probability measured with neutrinos and antineutrinos



Events ($\sin^2(2\theta_{13})=0.095$)	v	anti-v
NC	19	10
ν_μ CC	5	<1
beam ν_e	8	5
Tot. BG	32	15
Signal	68	32

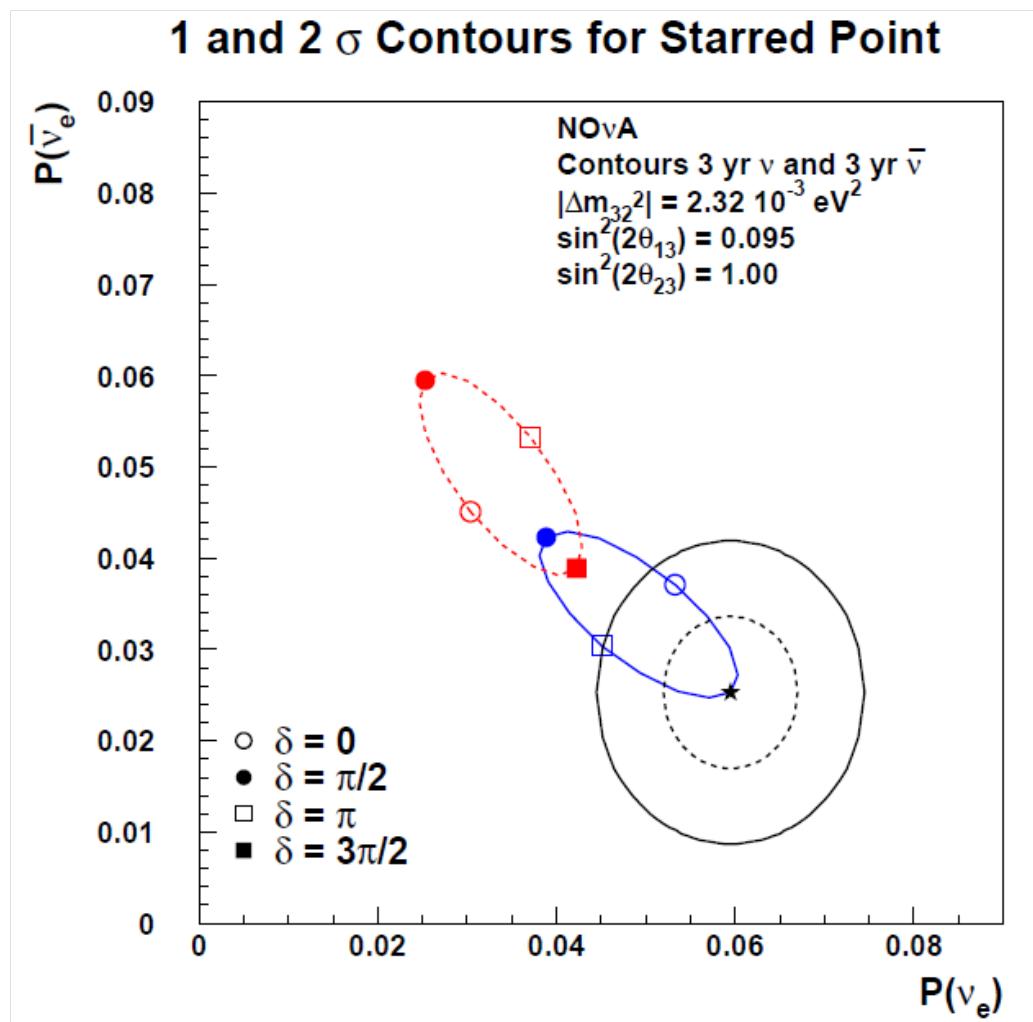
“Representative” event counts from 3 years neutrinos+3 years antineutrinos



HOW ITS DONE

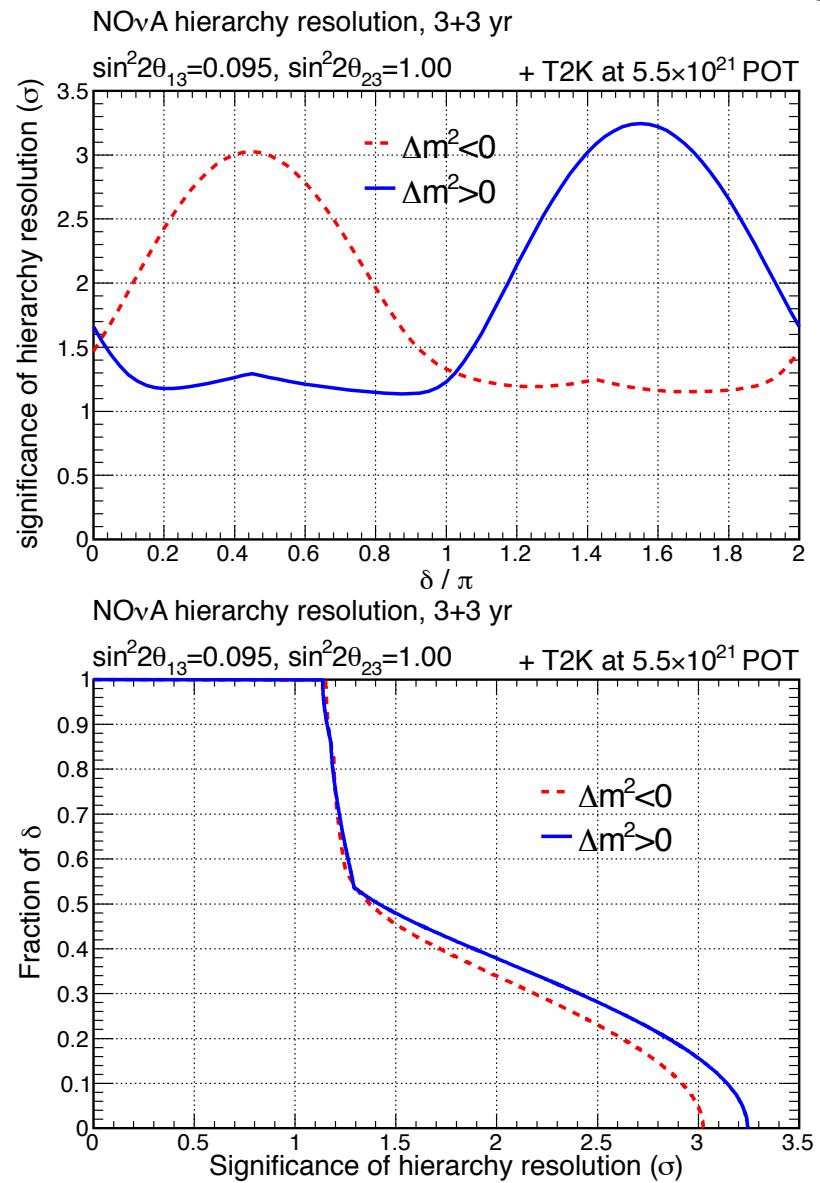
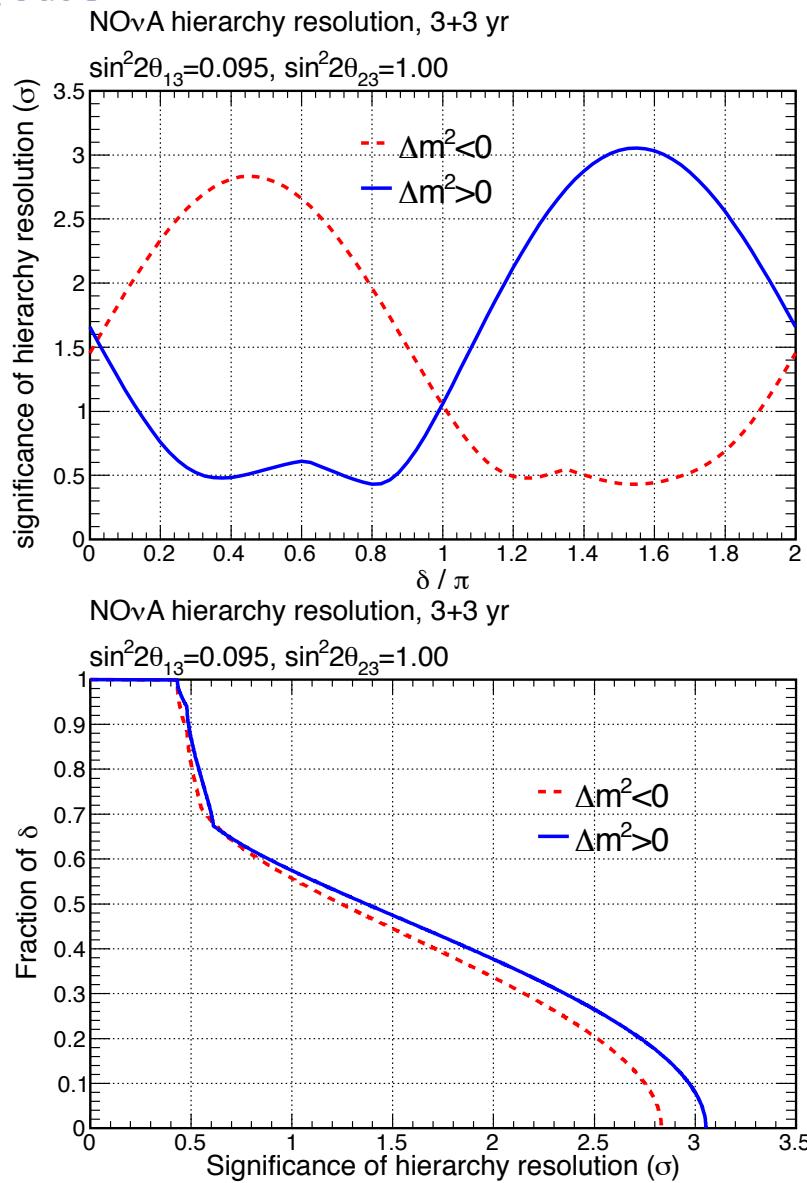


- Compare oscillation probability measured with neutrinos and antineutrinos





MASS HIERARCHY SENSITIVITY

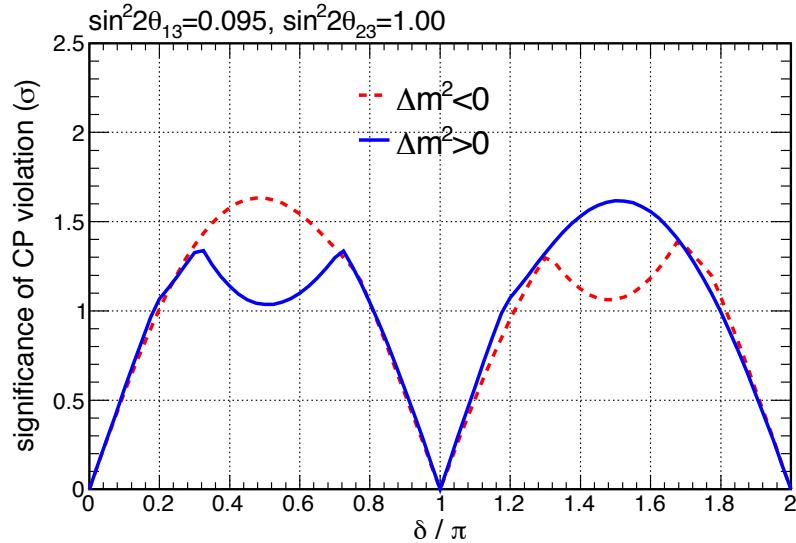




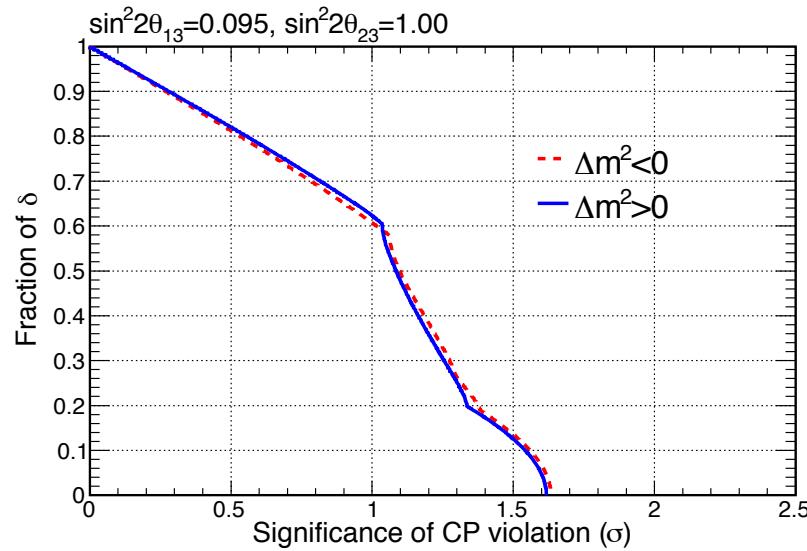
DELTA CP SENSITIVITY



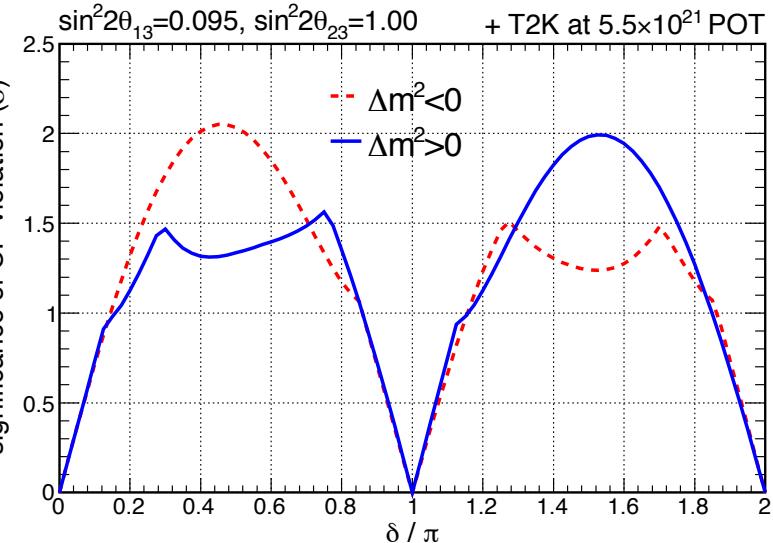
NOvA CPV determination, 3+3 yr



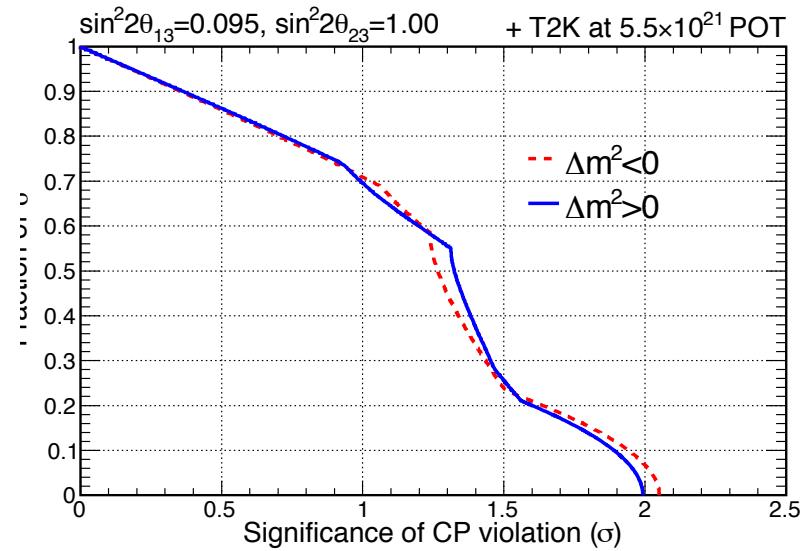
NOvA CPV determination, 3+3 yr



NOvA CPV determination, 3+3 yr

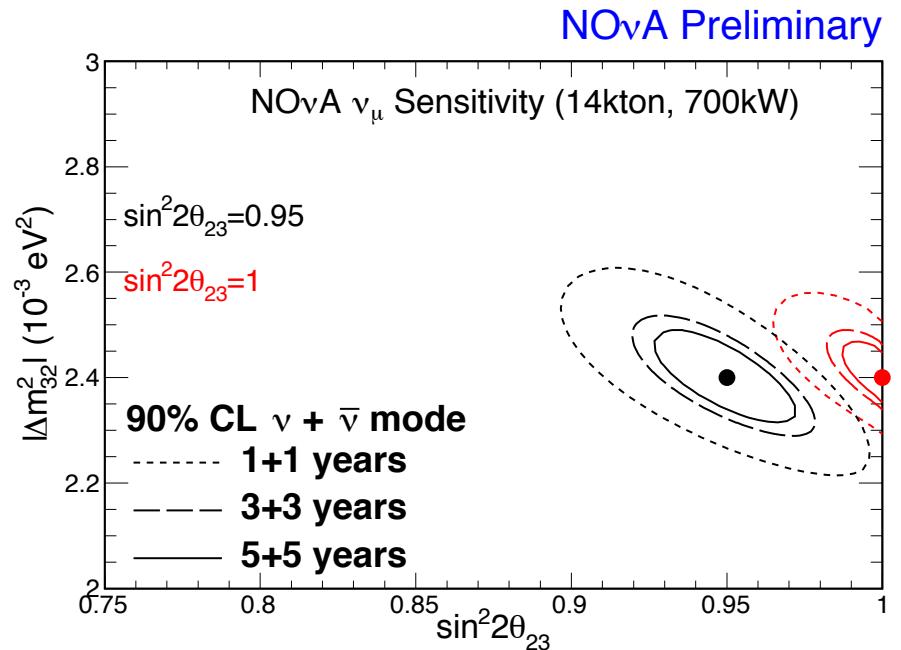
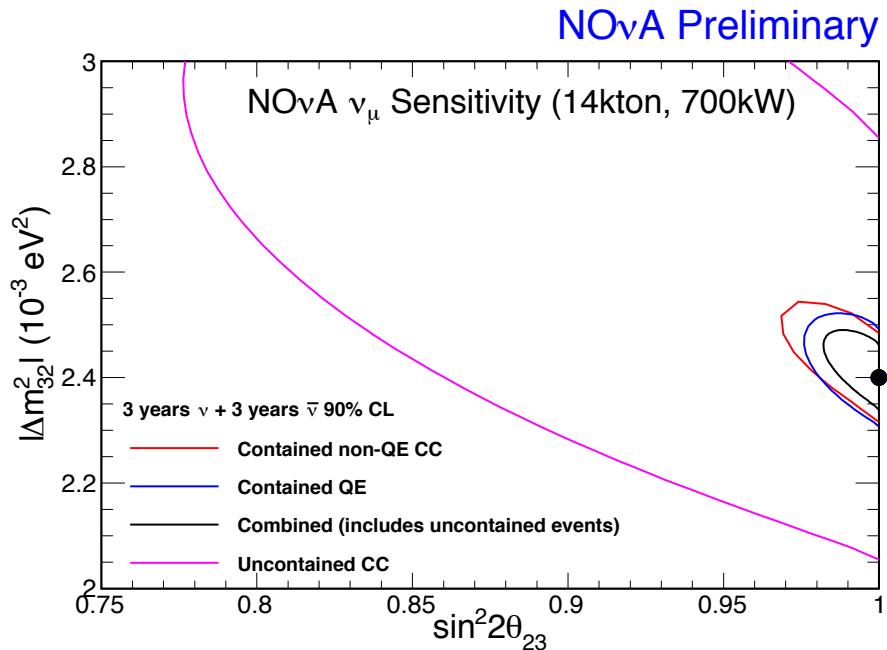


NOvA CPV determination, 3+3 yr





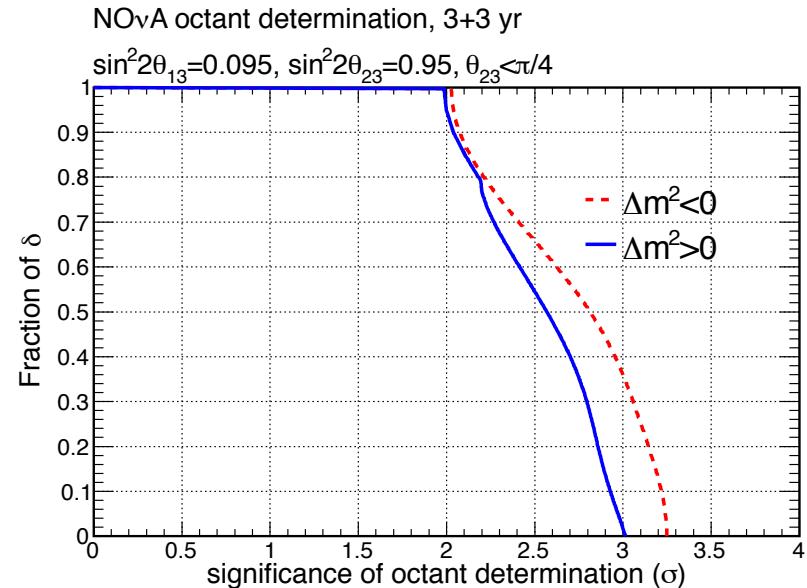
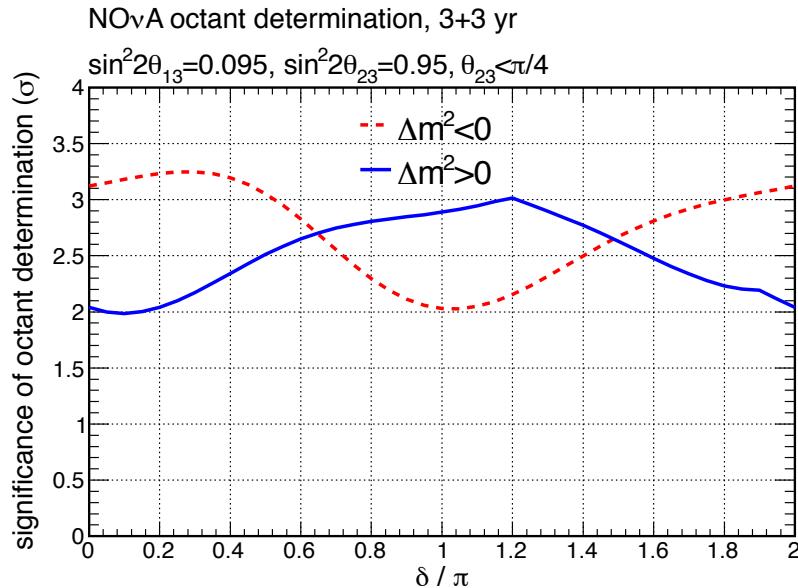
MUON NEUTRINO DISAPPEARANCE



- Percent level uncertainty on atmospheric mixing parameters in 3+3 years
- Exclude maximal mixing in 1+1 year at 90% if $\sin^2(2\theta)=0.95$ (statistical sensitivity only)



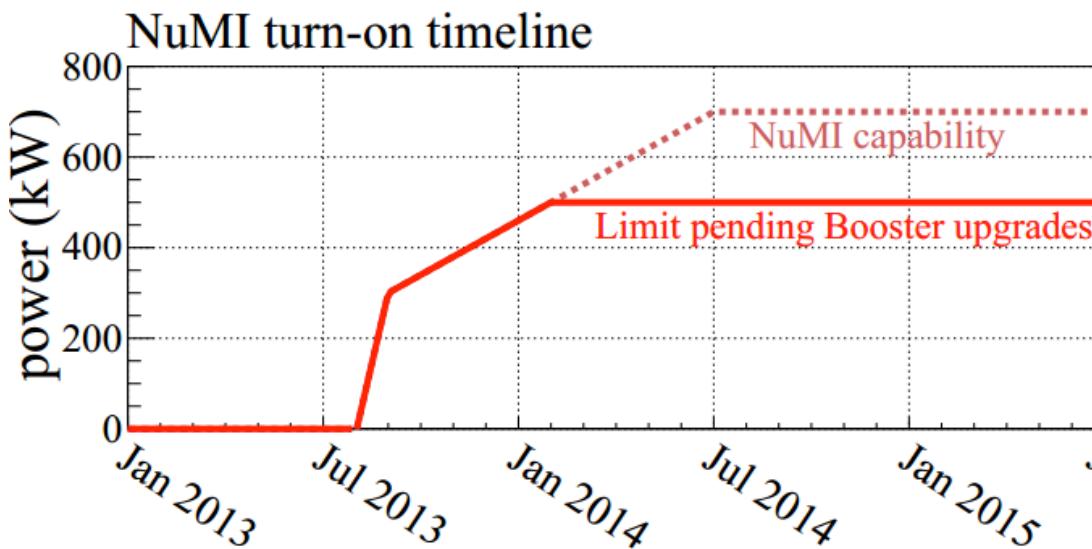
OCTANT SENSITIVITY



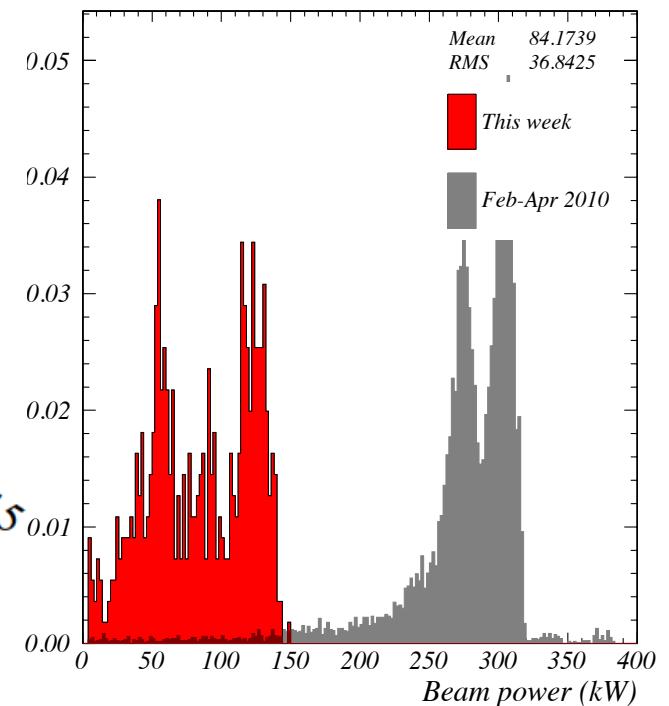
- Combines appearance and disappearance
- For lower octant
- Upper octant slightly better



BEAM STATUS



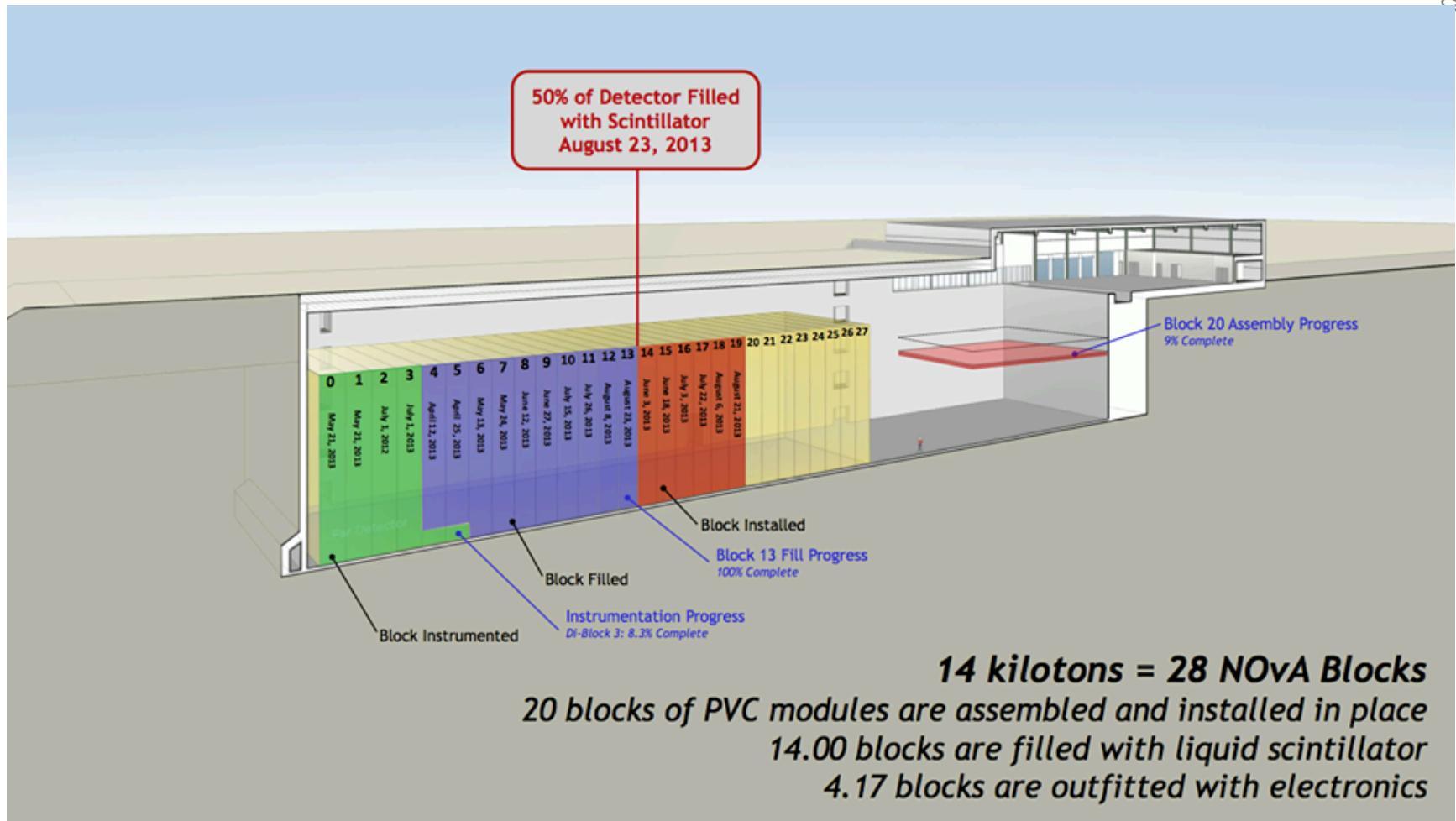
Week ending 00:00 Monday 09 September 2013



- First beam on Sept. 4!
- First year power expected to be 500 kW
 - Limited by Booster until RF upgrades completed



DETECTOR STATUS



- FD complete ~May 2014
- First half ND ready early 2014
- Commissioned portion of detector can operate independently of portion being commissioned

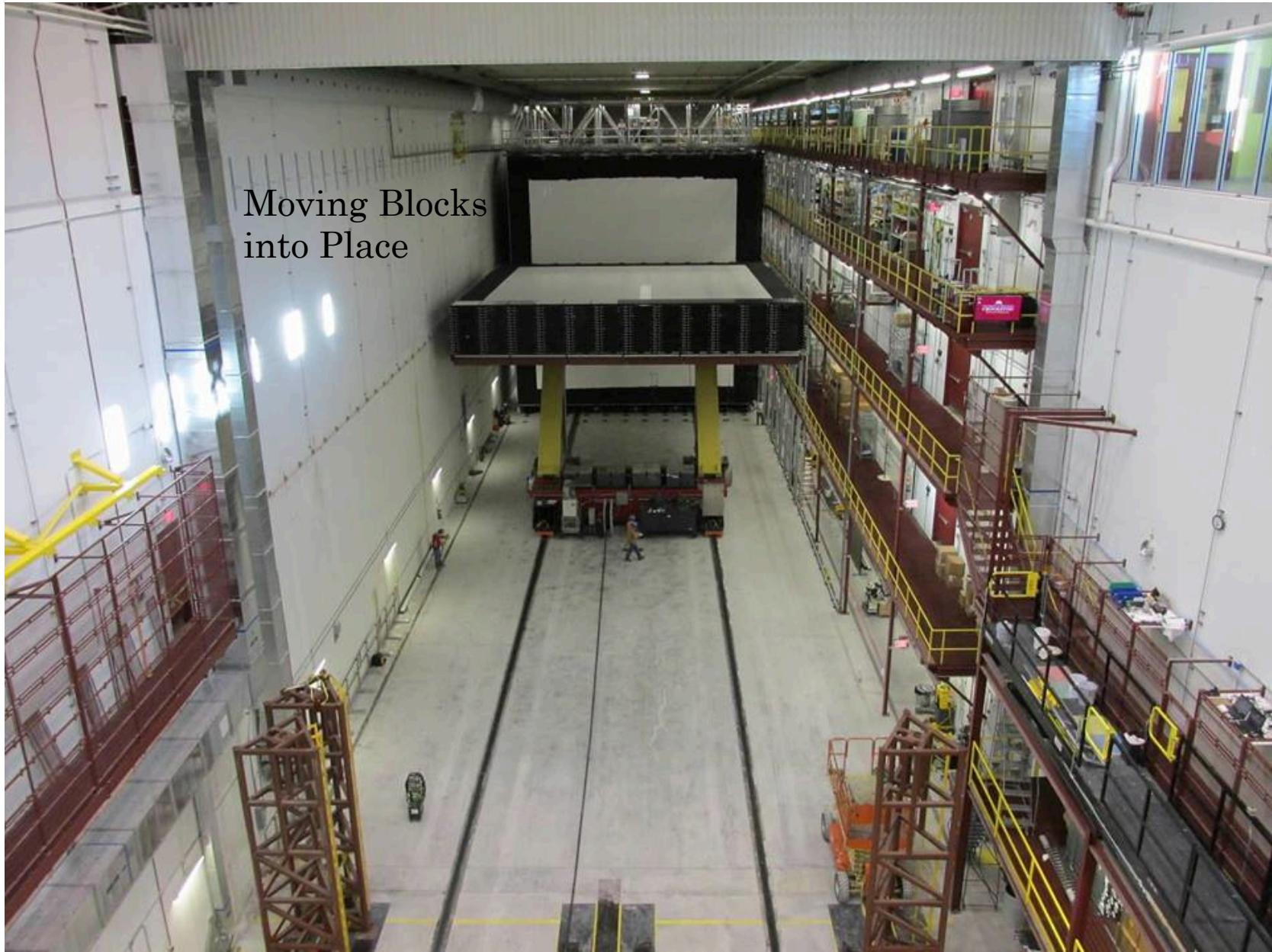


DETECTOR STATUS





DETECTOR STATUS



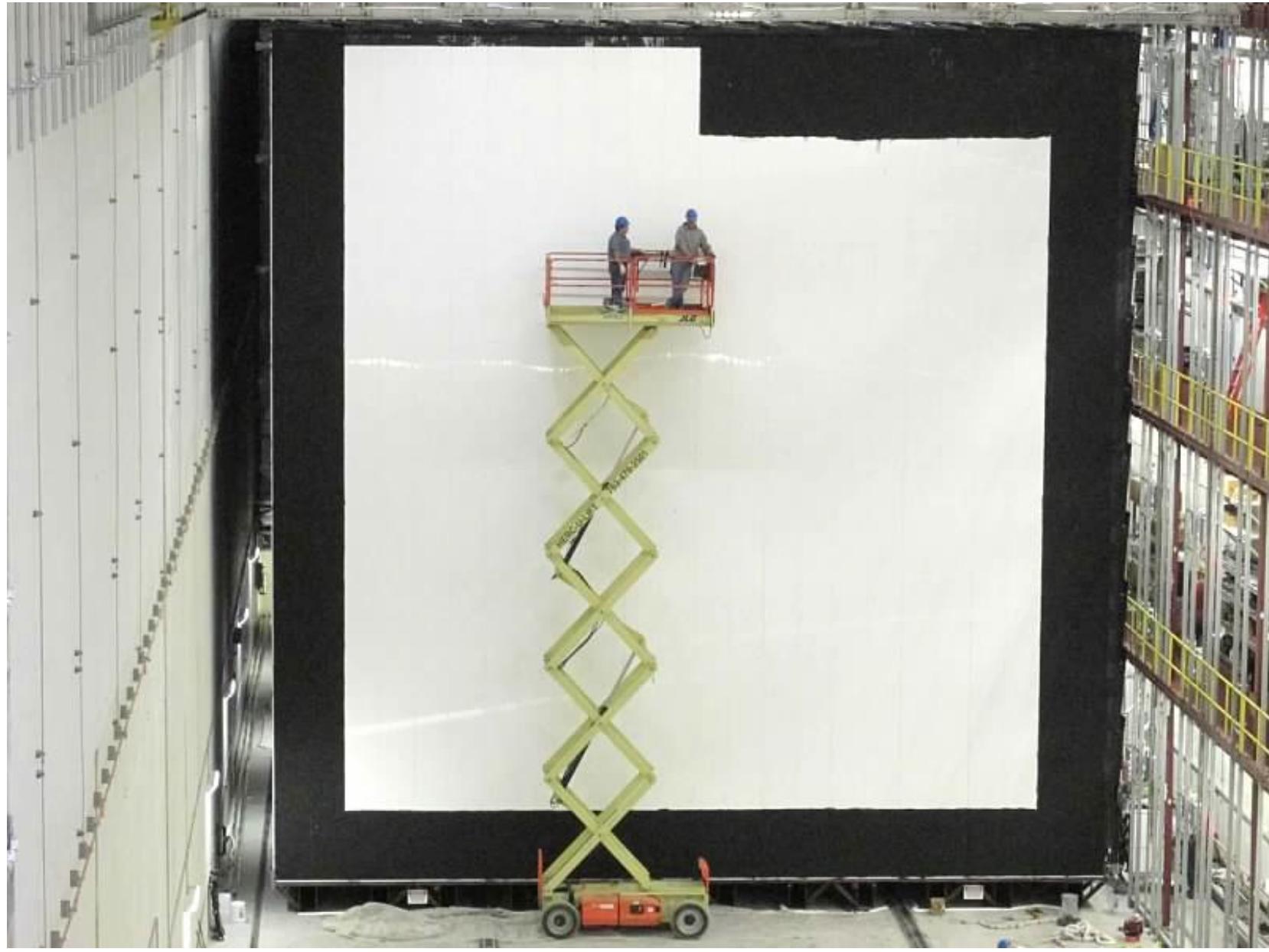


DETECTOR STATUS





DETECTOR STATUS



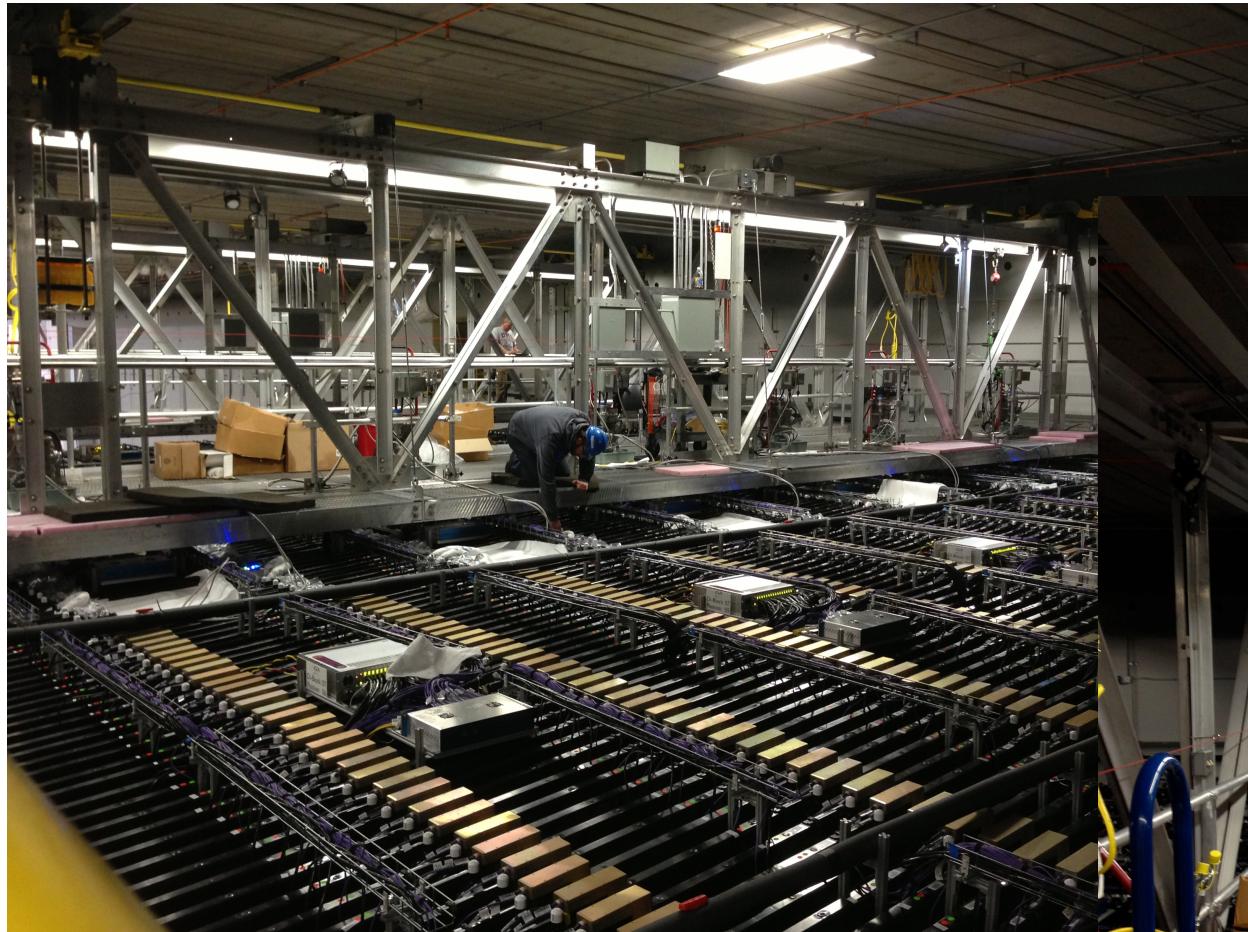


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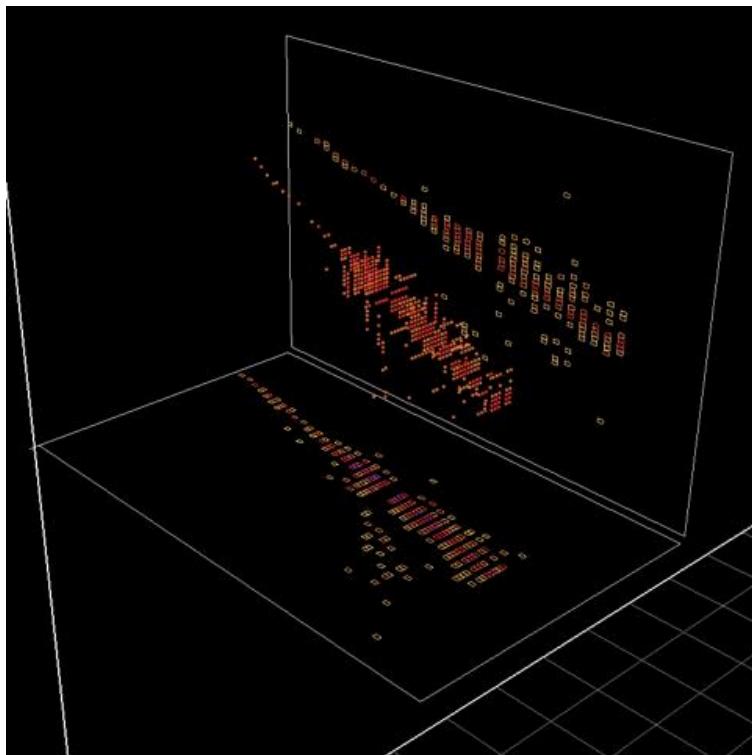


DETECTOR STATUS

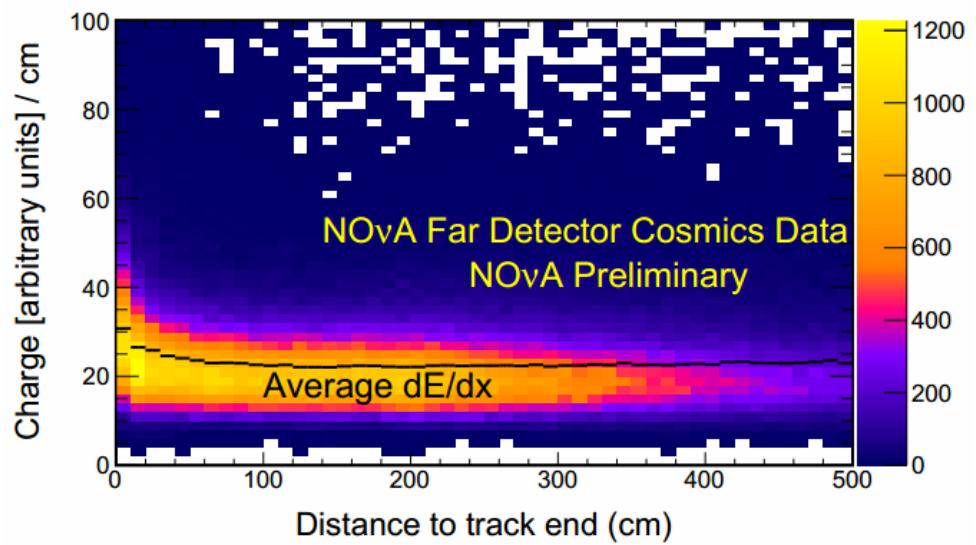
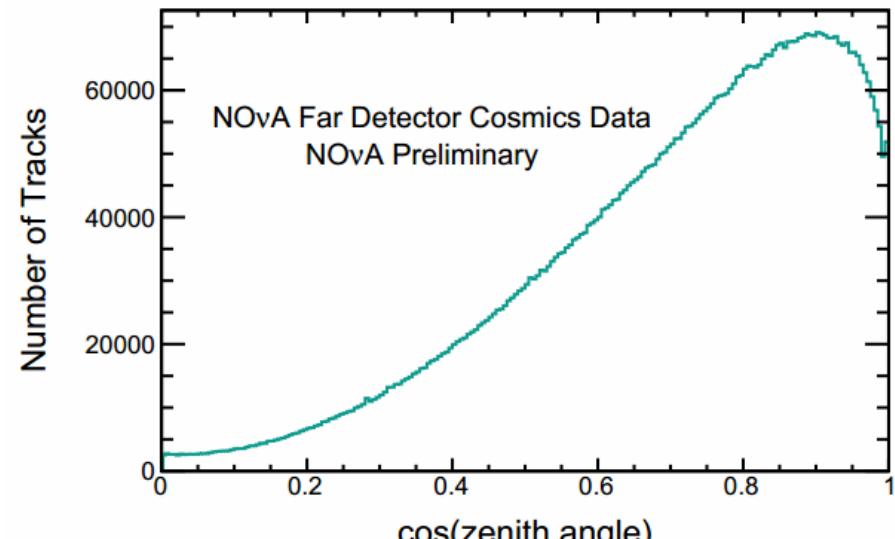




FAR DETECTOR DATA



- 2 ktons instrumented
- We see cosmics!
- Reconstruction algorithms tested on cosmic ray data collected

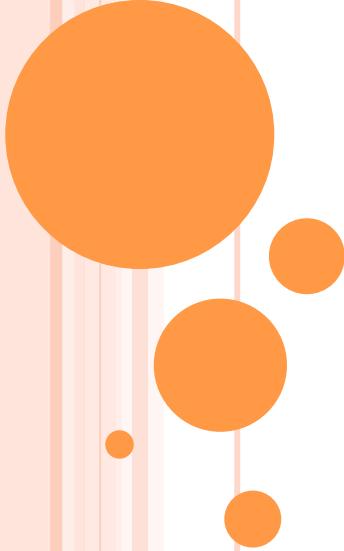




SUMMARY



- NOvA is in the right place at the right time to constrain
 - mass hierarchy
 - delta CP
 - octant
- We have Beam!
- Detector construction proceeding
- Stay Tuned! The fun has just begun.



BACK UP



NEUTRINOS HAVE MASS!



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
 - Flavor States: creation and detection
 - Mass States: propagation

- A neutrino created as one flavor can later be detected as another flavor, depending on:
 - distance traveled (L)
 - neutrino energy (E)
 - difference in the squared masses ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)
 - The mixing amplitudes ($U_{\alpha j}$)



THE PMNS MIXING MATRIX



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- (12) Sector: reactor + solar, L/E~15,000 km/GeV

$${}^{\dagger} \Delta m_{21}^2 = 7.50_{-0.20}^{+0.19} \times 10^{-5} \text{ eV}^2 \quad \tan^2 \theta_{12} = 0.452_{-0.033}^{+0.035}$$

- (23) Sector: atmospheric and accelerator, L/E~500 km/GeV

$${}^{\dagger\dagger} |\Delta m_{32}^2| = 2.32_{-0.08}^{+0.12} \times 10^{-3} \text{ eV}^2 \quad {}^* \sin^2(2\theta_{23}) > 0.96 \text{ (90% C.L.)}$$

- (13) Sector: reactor and accelerator, L/E~500 km/GeV

$${}^{**} \sin^2(2\theta_{13}) = 0.090_{-0.009}^{+0.008} \text{ (stat.+syst.)}$$

[†]PRD 83.052002(2011)

^{††}PRL 106. 181801(2011)

^{*}SuperK Preliminary, Nu2010

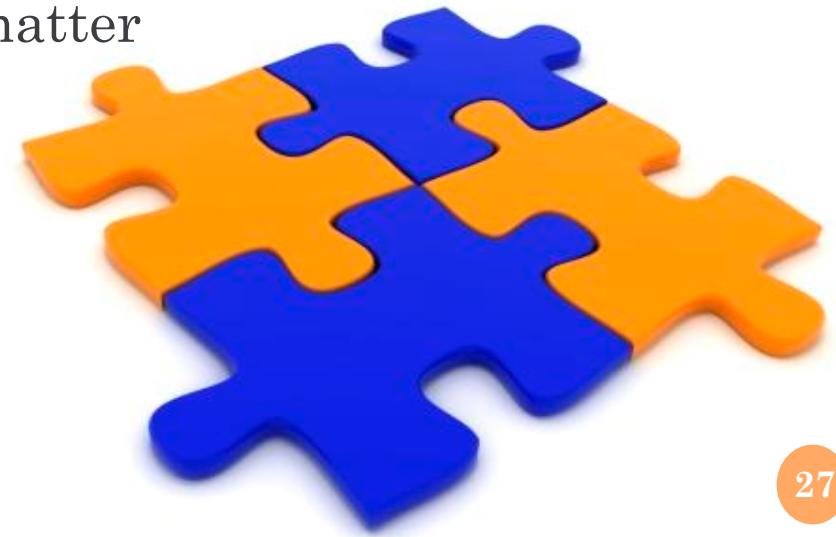
^{**}Daya Bay Preliminary, NuFact2013



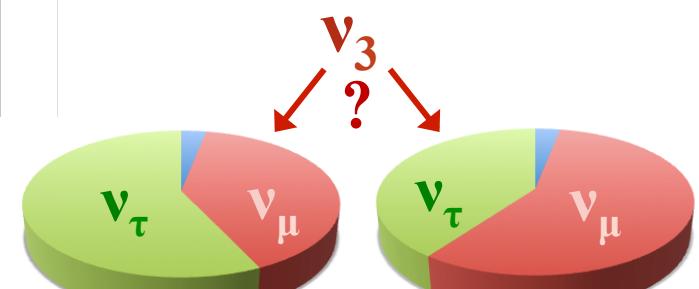
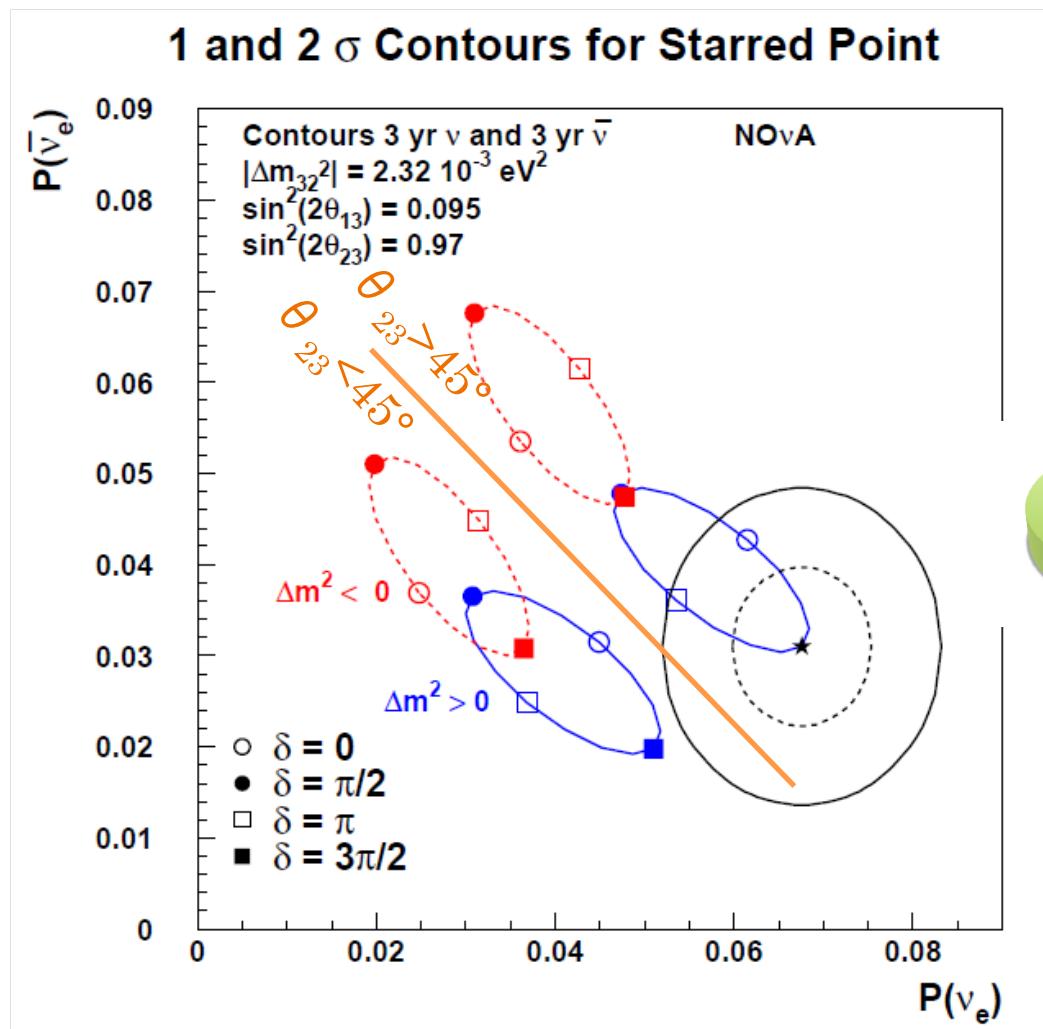
WHY MEASURE ALL THESE ANGLES?



- Precision measurements provide a valuable constraints on neutrino oscillation model
- Open Questions:
 - What are the masses of the neutrinos?
 - What is the nature of neutrino mass?
 - Which neutrino is most massive?
 - Why is lepton mixing much larger than quark mixing?
 - Is there an underlying symmetry to the mixing matrix?
 - Is there CP violation in the lepton sector?
Is it big enough to account for matter vs. antimatter asymmetry?
- Small neutrino mass suggests a heavy partner—Neutrinos provide a window to physics at the GUT scale!

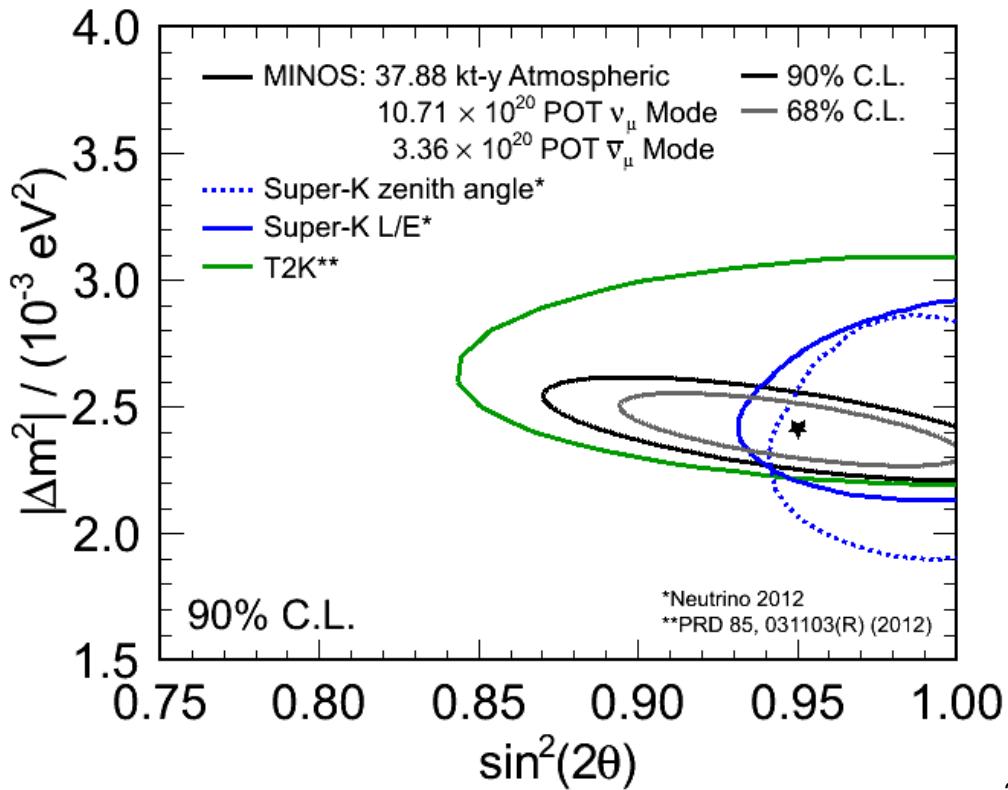


- Compare oscillation probability measured with neutrinos and antineutrinos

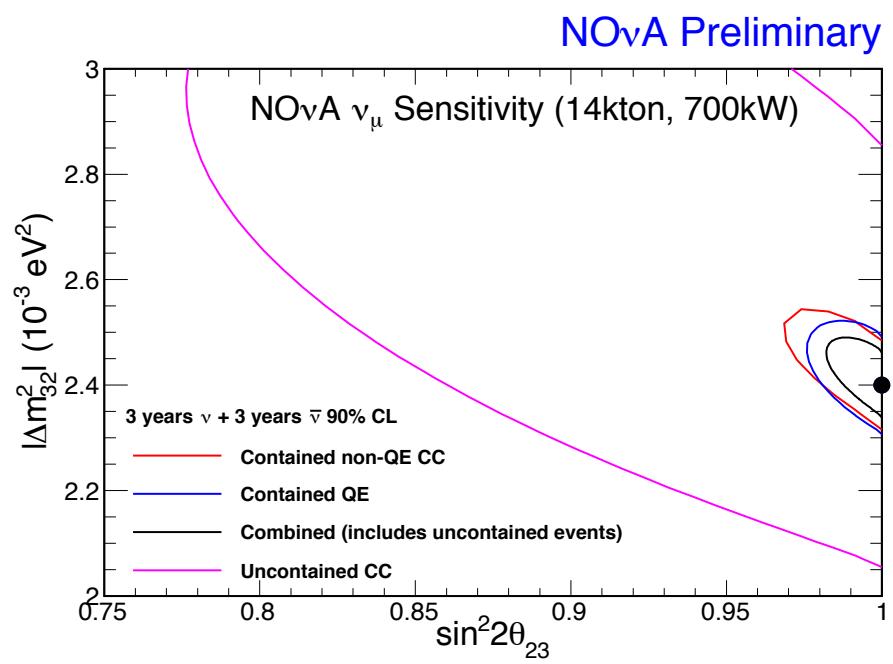




MINOS NOVA COMPARISON



P. Vahle, TAUP 2013





LESSONS LEARNED



Top View



Side View

- 22% of module manifolds developed cracks during detector installation
 - “Splints” to fix NDOS
 - Changes to pressure testing
 - Redesign of manifolds
- APDs and oil do not mix
 - plan to coat APDs with epoxy
 - revamped procedures to ensure cleanliness is maintained during industrial scale installation

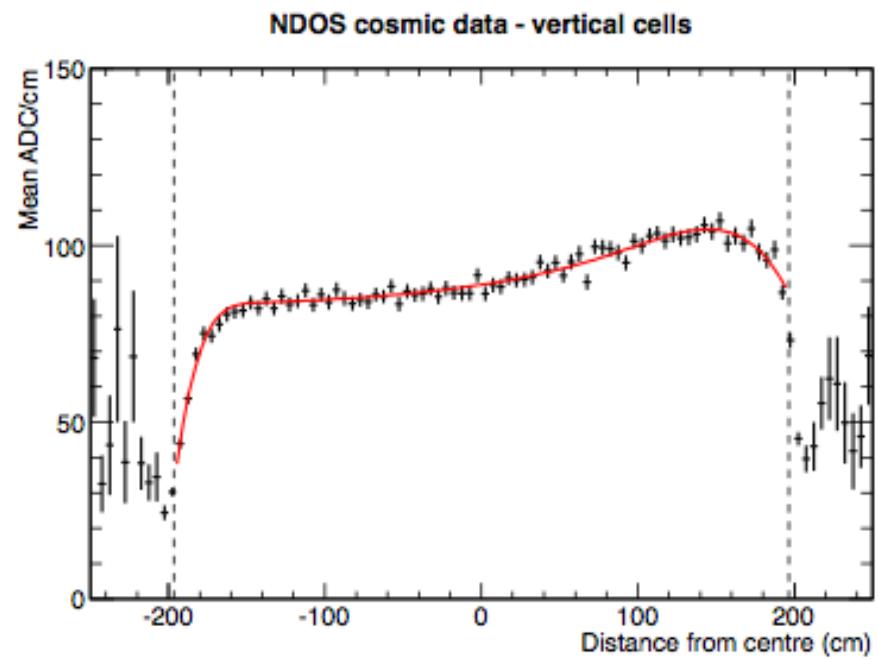
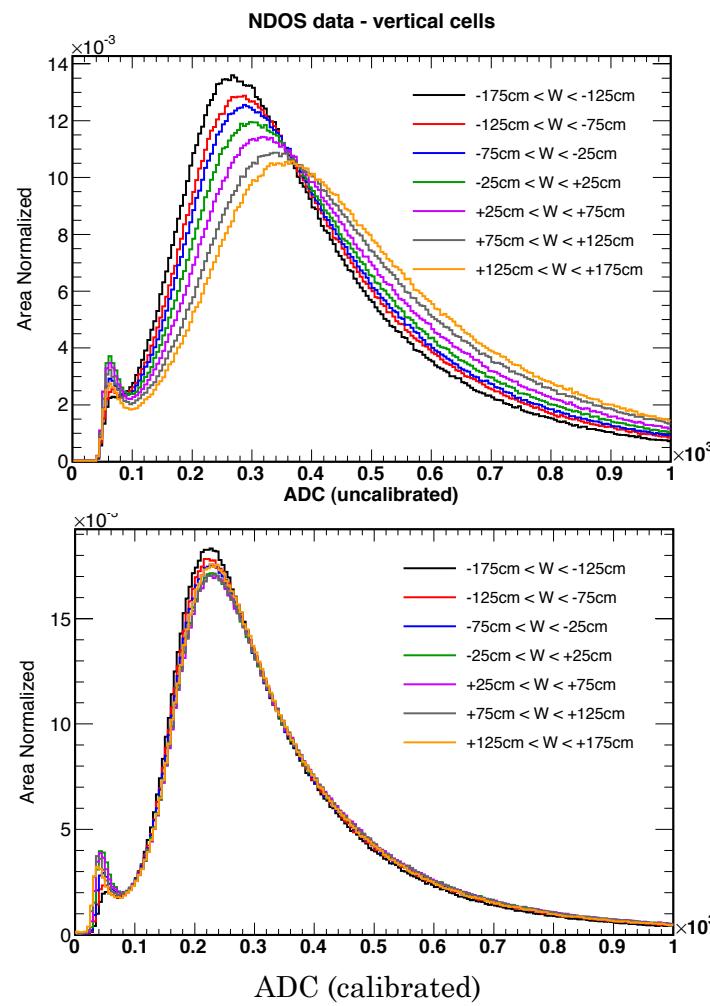




CALIBRATION



- Cosmic muons provide intra-detector calibration source

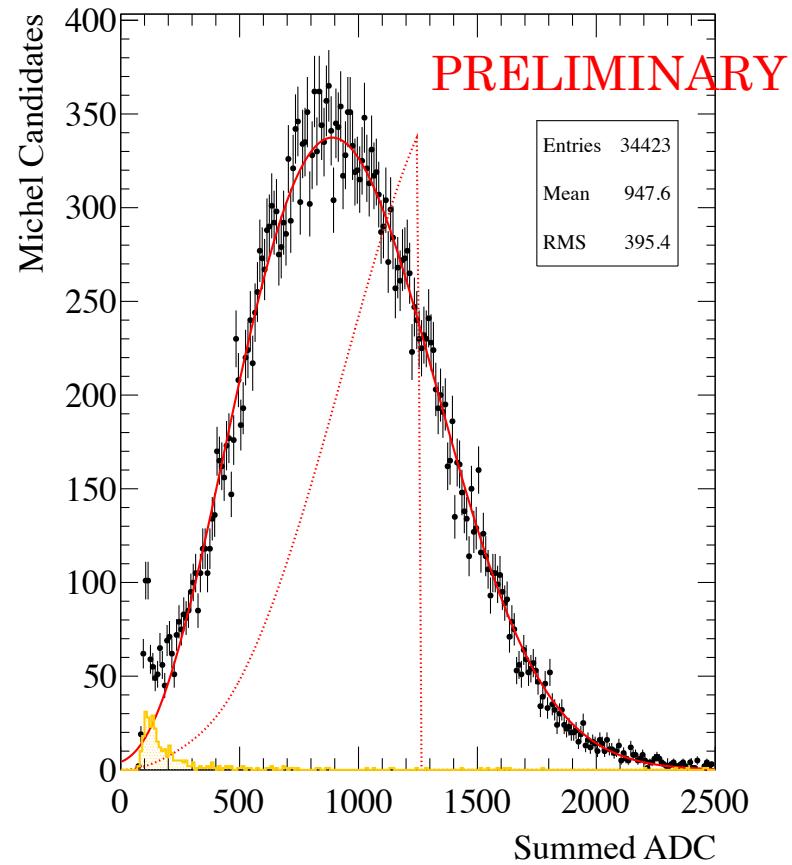
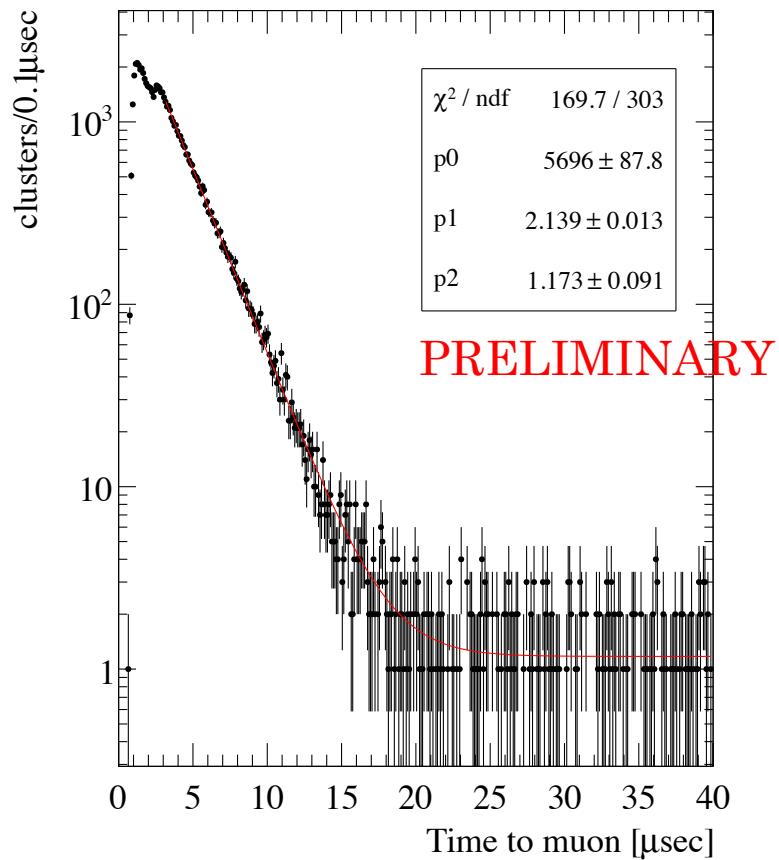




MICHEL ELECTRONS

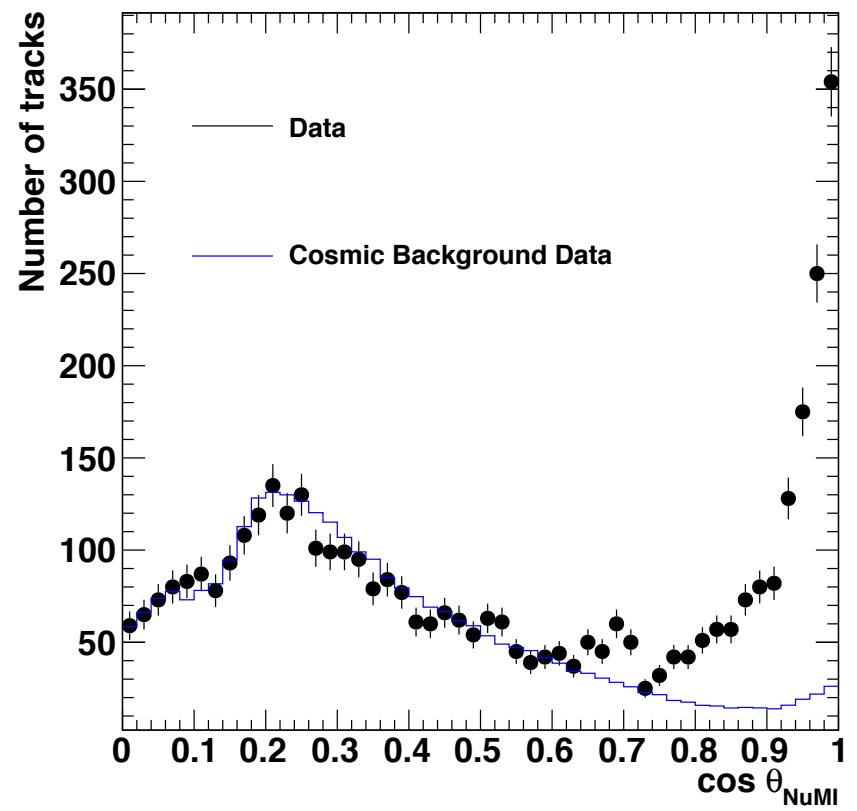
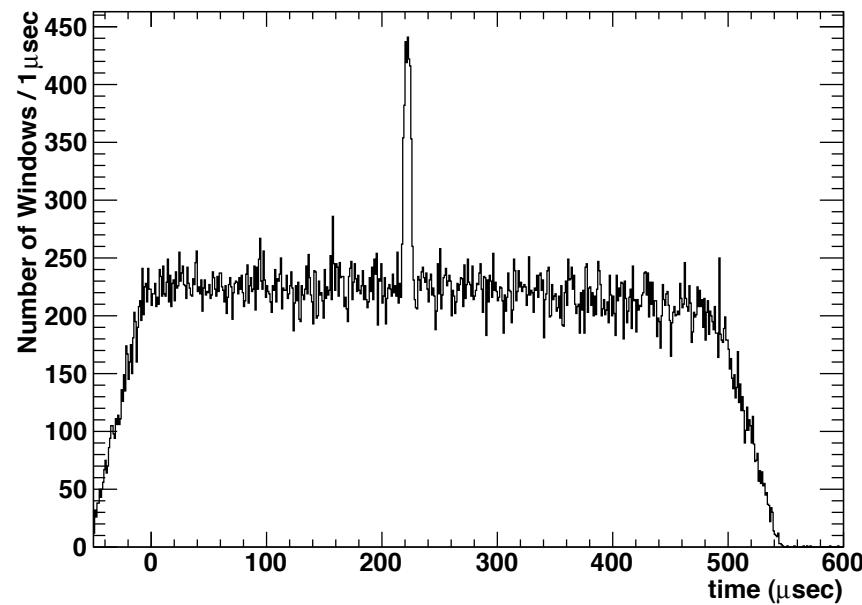


- Use Michel electrons for electro-magnetic energy calibration





FINDING NUMI NEUTRINOS

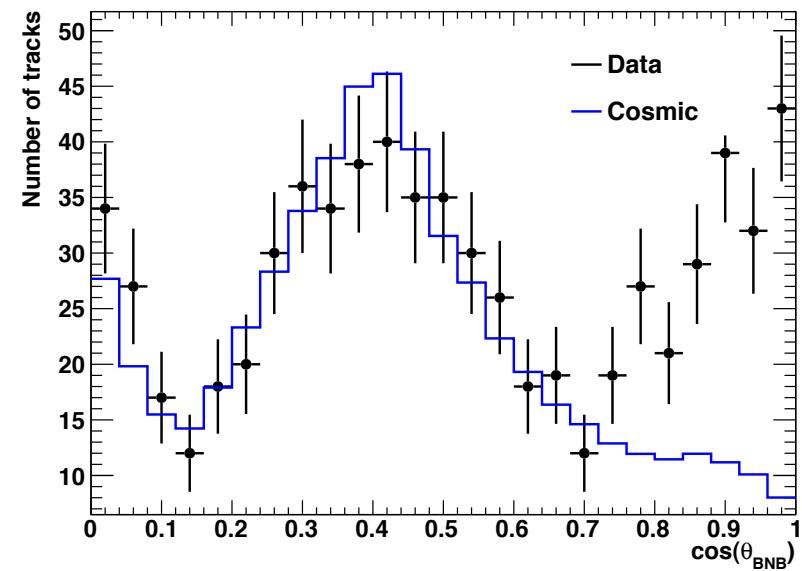
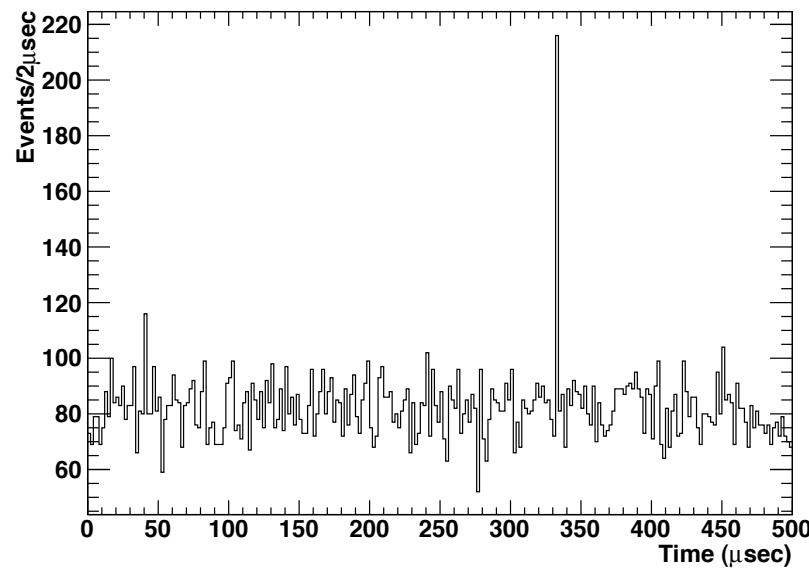


- 110 mrad off NuMI axis
- 5.6×10^{19} POT reverse horn current beam, 1001 NuMI events (69 cosmic BG)
- 8.4×10^{18} POT forward horn current beam, 253 NuMI events (39 cosmic BG)





FINDING BOOSTER NEUTRINOS

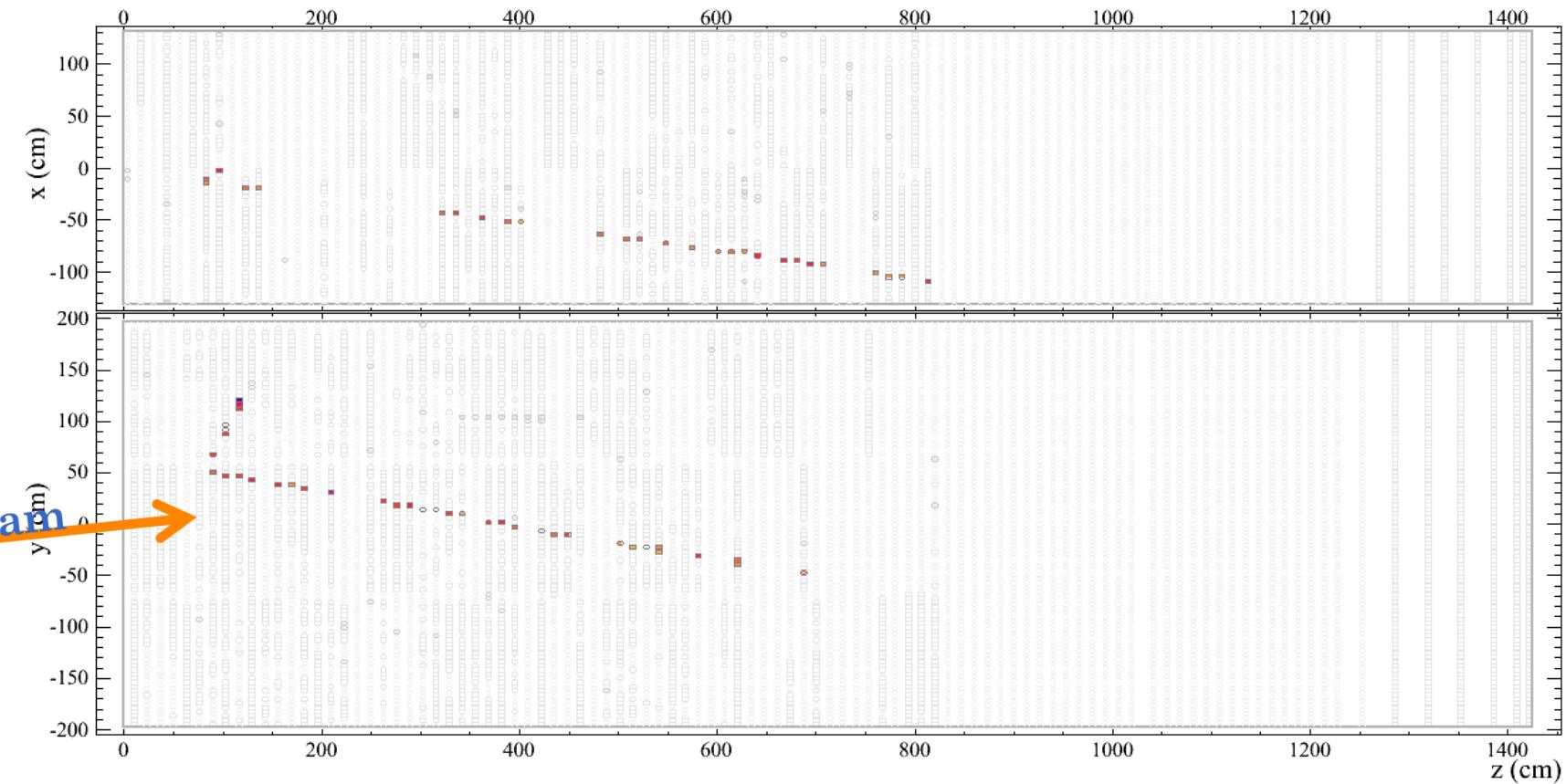


- NDOS nearly on Booster axis
- Detector rotated wrt axis
- 3×10^{19} POT, 222 booster events (92 cosmic BG)





NEUTRINOS

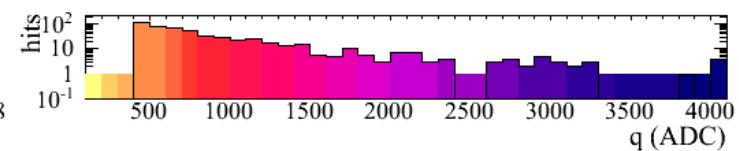
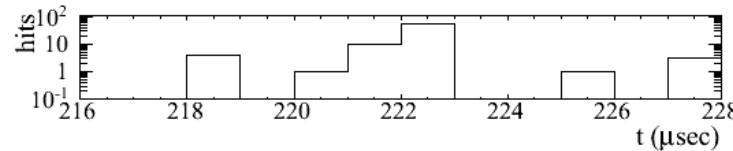


NOvA - FNAL E929

Run: 10893/8

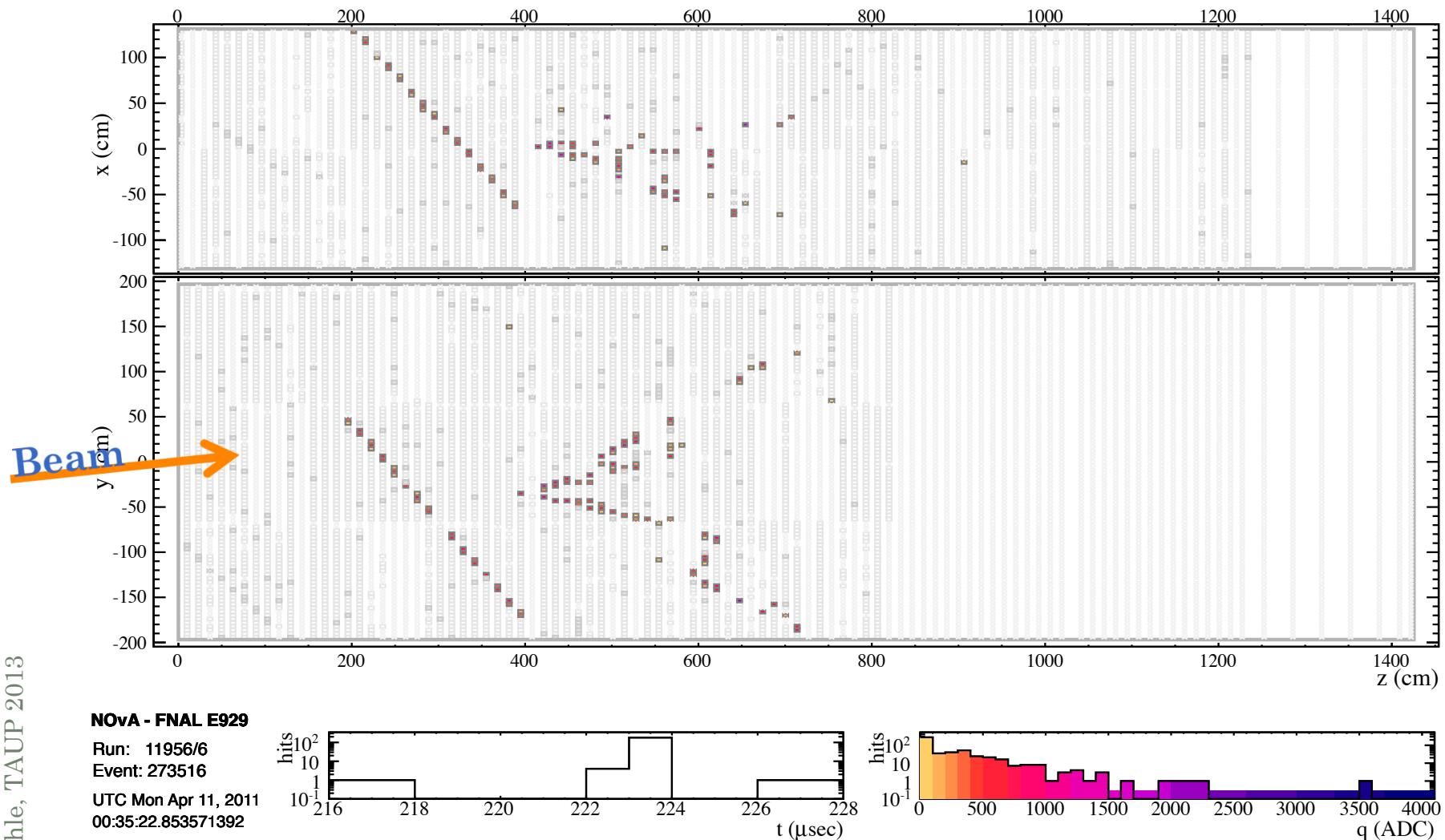
Event: 314724

UTC Tue Dec 21, 2010
11:48:18.997623872



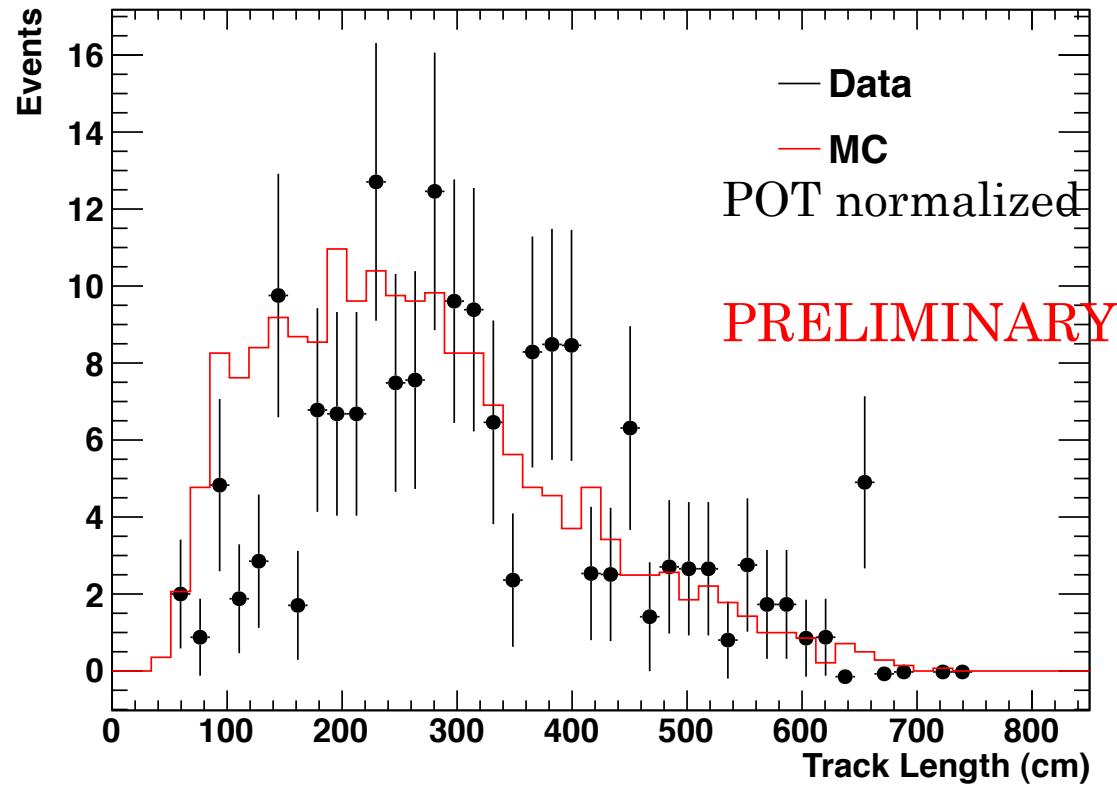


NEUTRINOS





COMPARISONS TO MC

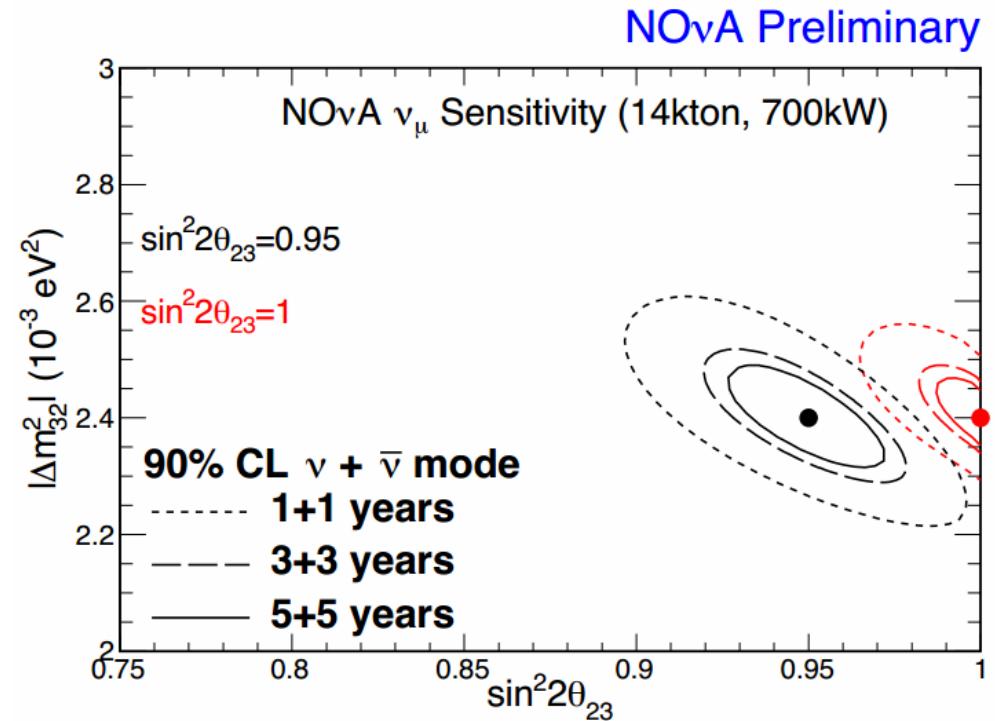
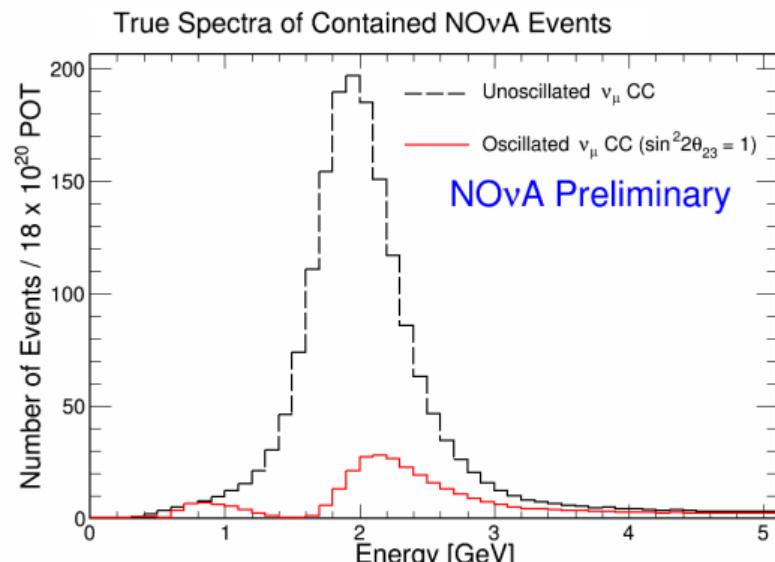


- Early look at contained events indicates NuMI MC event rate agrees with data





MUON NEUTRINO DISAPPEARANCE

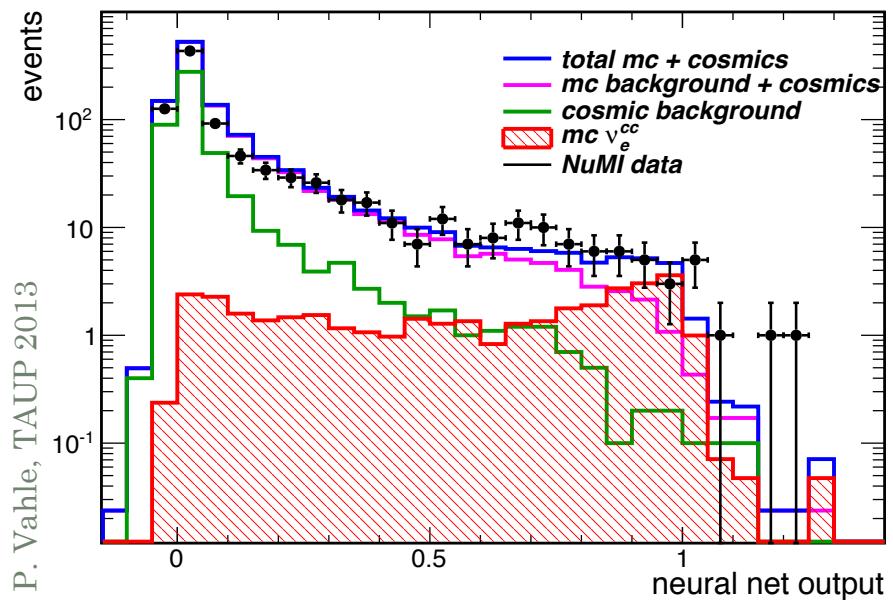


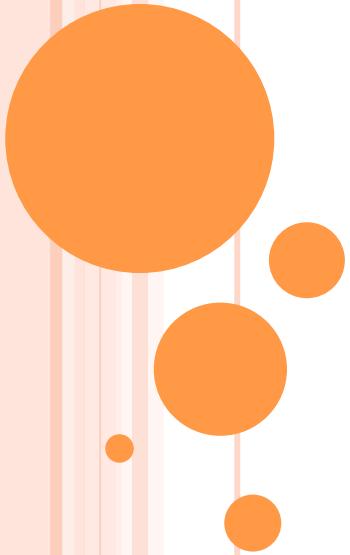
- ❑ If $\sin^2 2 \theta_{23} = 0.95$, able to exclude (at 90% CL) maximal θ_{23} after 1+1 years



NDOS

- Prototype detector in the NuMI and Booster beams
- Benchmark simulation/reconstruction against real neutrino events
- We can find the 2% electron neutrino contamination of the beam!





ENUMI

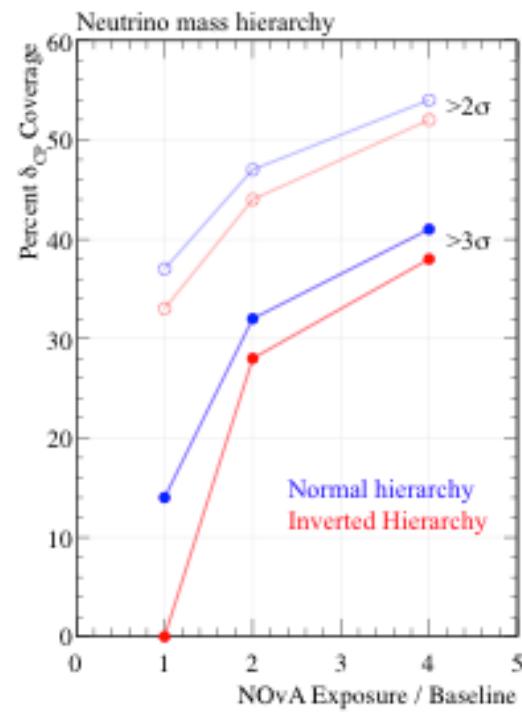


Figure 2: The percent of δ_{CP} values for which NOvA can resolve the neutrino mass hierarchy at 2 and 3 σ C.L.

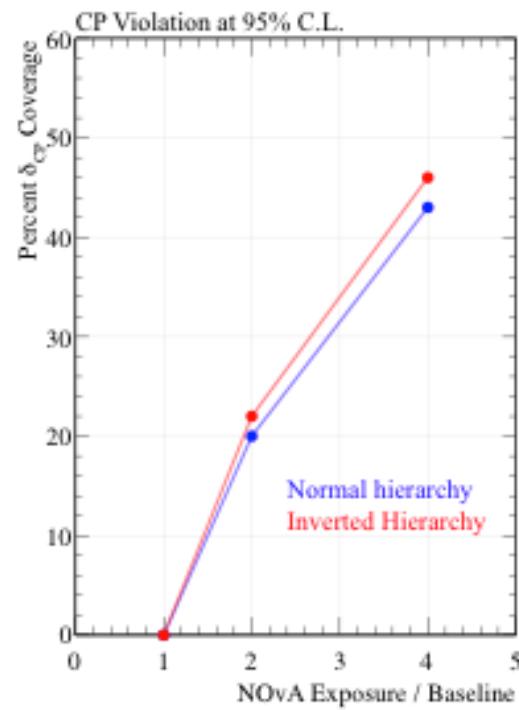


Figure 3: The percent of δ_{CP} values for which NOvA can establish CP violation at 95% C.L. or better.



RADAR



- Add LAr detector at Ash River

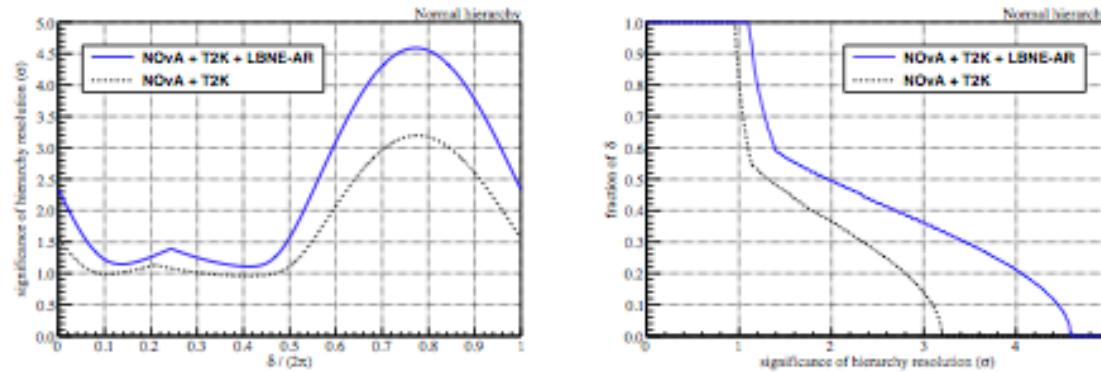


Figure 1: The significance of hierarchy resolution for NO ν A + T2K alone (black dashed) and with LBNE-AR added (blue solid), shown both as a function δ (left) and in terms of the fraction of δ values covered at a given confidence level. Normal hierarchy and maximum mixing are used.

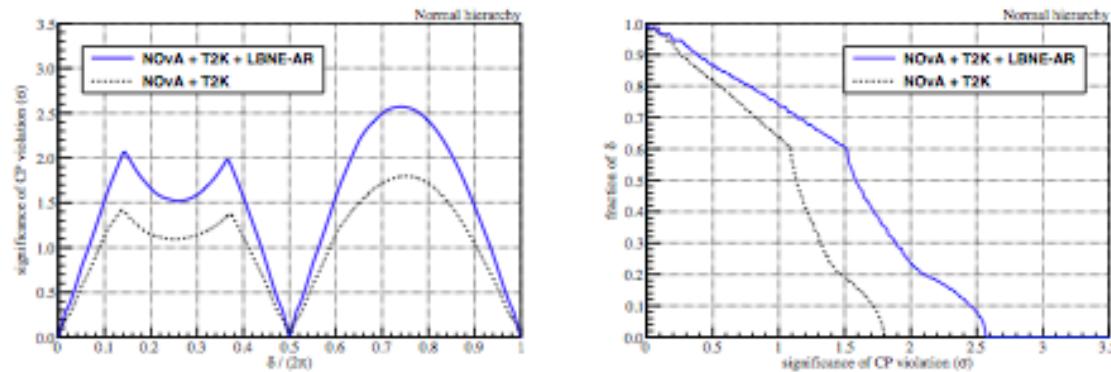


Figure 2: The significance of CP violation for NO ν A + T2K alone (black dashed) and with LBNE-AR added (blue solid), shown both as a function δ (left) and in terms of the fraction of δ values covered at a given confidence level. Normal hierarchy and maximum mixing are used.

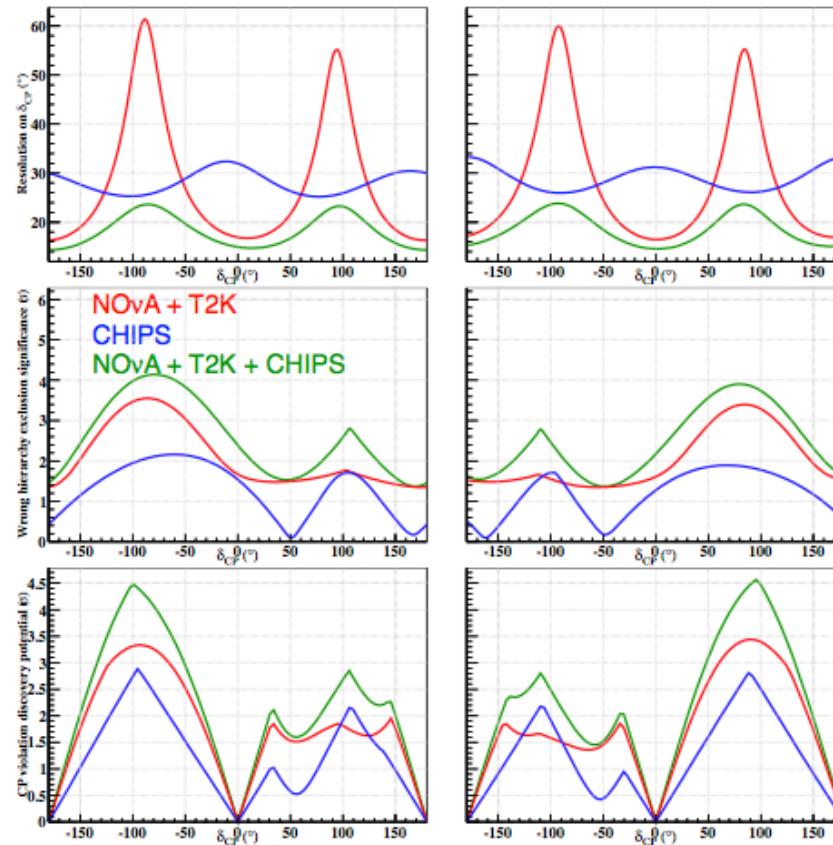


Figure 3: CHIPS physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOvA ($5+5y$) and T2K ($8.8e21 \text{ POT}$), and CHIPS ($3+3y$). (Top) δ_{CP} resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOvA and T2K, the blue line is CHIPS and the green is the combination.

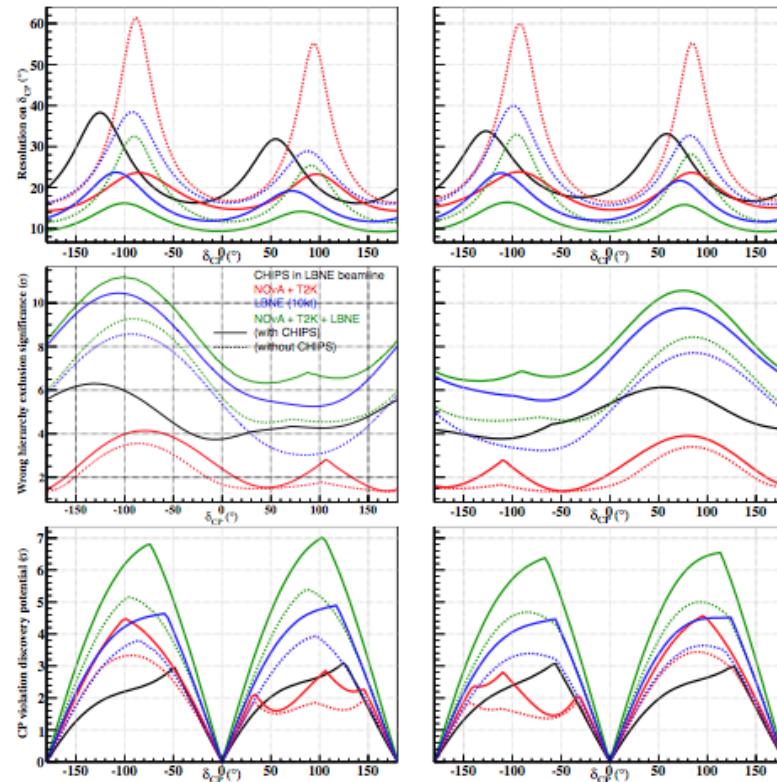


Figure 8: Physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOvA+T2K, 10 kton LAr LBNE, and CHIPS in the LBNE beam at 20 mrad. (Top) δ_{CP} resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOvA and T2K, the blue line is a 10 kton LAr detector on-axis in the LBNE beam, and the green is the combination of those experiments. Solid black line is for CHIPS, from both a NuMI and LBNE run. Dotted lines show each experiment (or combination of experiments) without a CHIPS run. Solid lines show the effect of adding CHIPS to the results.